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ABSTRACT

This instructional manual contains 11 learning activity packets for use in a workshop on photovoltaic converters. The lessons cover the following topics: introduction; solar radiation--input for photovoltaic converters; photovoltaic cells; solar electric generator systems; characteristics of silicon cells; photovoltaic module source resistance; photovoltaic converter output--fix position, Azimuth tracking, and storage system; and photovoltaic converter efficiency. Each learning activity packet lists prerequisites, purpose, and competencies to be developed and contains information sheets, illustrations, and learning activities. A list of equipment needed in a photovoltaic mobile teaching laboratory and information about operation and design of solar electric generator systems also are included in the manual. (KC)

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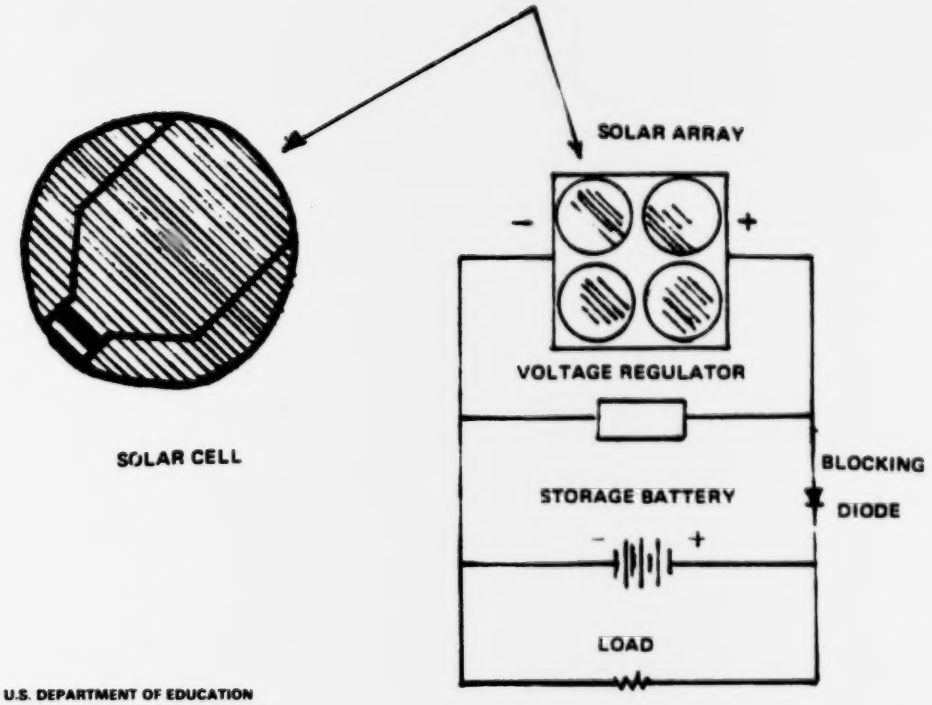
PHOTOVOLTAIC:

Instructional Manual

Writer: Dr. Herbert J. Auer



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1985

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The North Dakota
High Technology Mobile Laboratory Project

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PHOTOVOLTAIC CONVERTERS

INSTRUCTION MANUAL

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*8	Photovoltaic Converter Output, Fix Position	1, 2 & 7
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Appendix A: Solar Electric Generator Systems, Principles of Operation and Design Concepts (Reading material from Solar Power Corporation.)

*These two experiments can be done in conjunction with one another. Each should be done twice, once near solar noon and once at early forenoon or late afternoon hours.

ACCESSORIES FOR THE PHOTOVOLTAIC CONVERTER UNIT
of the
High Technology Mobile Laboratory

The photovoltaic converter unit is provided with a variety of acessories which are meant to enhance its versatility and the information students can gain when conducting the learning activities of this manual. The following descriptive listing also provides the instructor with an inventory of items to permit a quick check of the unit's completeness prior to moving the laboratory to another school.

A. Main Items

1. The loading/monitoring circuitry, the battery and the fan/light assembly (useable for simple demonstrations) are secured to the cart. Notice that the battery is secured with a bracket - to prevent its easy removal!

2. The photovoltaic module with frame can be removed from the cart by removing the bolts (with wing burrs) at the front and rear of the frame's base. This feature makes it possible to leave the module outdoors while having the loading/monitoring circuitry, battery, etc., indoors during cold weather.

B. Accessory Items

1. Two (2) module carrying bars: These are located in holders along the vertical frame members. These bars can be slid horizontally through the square tubes at the frame's corners, secured with set screws, and used to carry and mount the module outdoors.

2. One (1) extension cord with polarized twist-lock connectors: This is for connecting the module to either the loading/monitoring circuitry or the fan/light assembly when the module is separated from the remainder of the unit. CAUTION: Notice that all of the polarized connectors are of the twist-lock type; they cannot be disconnected by simply pulling on the cord!

3. One (1) insolation meter: This is used for measuring light radiation. It if a sensitive instrument and must be treated accordingly.

4. One (1) angle-of-incidence meter: This is used to measure the angle at which solar beam radiation strikes a surface.

5. One (1) metric ruler: This is for determining the size of an individual photovoltaic cell.

6. Two (2) module covers, one opaque and one translucent: These are used to simulate night-time darkness and day-time partial (ultraviolet) blockage of solar radiation, respectively, and to cover the module when not in use and during transport, at which times the covers are secured by a rubber strap.

7. One (1) single-cell and one (1) three-section rectangular column-of-cells cover: These are provided to simulate a reduction of the effective cell area being exposed to solar radiation.

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HIGH TECHNOLOGY MOBILE LABORATORY

Learning Activity Packet

MAJOR INSTRUCTIONAL UNIT: Photovoltaics

LEARNING ACTIVITY PACKET (LAP) NUMBER: 1

LAP TITLE: Introduction

PREREQUISITE LAP (S) : None

LAP PURPOSE: To present background information regarding the basic terminology and some limitations and uses of photovoltaics.

COMPETENCIES TO BE DEVELOPED:

1. Be able to define various terms pertaining to the field of photovoltaic converters.
2. Be able to list a variety of uses of photovoltaic devices.

BACKGROUND INFORMATION

Introduction

This series of Learning Activity Packets (LAPs) will guide you through and provide information on the theory, make-up, measurements, and potential uses of one type of alternate energy, through use of a photovoltaic converter. This LAP provides definitions of basic terms used in later activities. These should be read, understood, and remembered so that the information in and activities of the later LAPs will be easier to follow and have more meaning.

The last part of this LAP contains a list of actual photovoltaic device uses. Also provided are some conditions and limitations which must be considered before assuming that a photovoltaic converter will fulfill a need for electrical power. These conditions and limitations are very important because, at the present time, there are relatively few locations and applications where a solar electric generator system's output can justify its cost compared to other electrical power sources.

Definition of Basic Terms

The following terms are defined with regard to the field of photovoltaics and/or electricity, as used in later LAPs. For those terms (words) which have a unit of measurement, the unit typically encountered in later LAPs is given just beyond the term itself.

1. Converter - A device which converts one form of energy, or power, to another form of energy, or power.
2. Current - Amperes, or Amps - A measure of the intensity of flow of electrical charge.
3. Diode - A semiconductor device, usually made of silicon, which permits charge flow in one direction only.
4. Input - That energy, or power, which enters a device, converter, or system.
5. Insolation - mW/cm^2, milliwatt per square centimeter - The radiation striking or falling on unit area of a surface.
6. Light - Radiated energy which travels in the form of waves; may include ultraviolet light, visible light and/or infrared wavelengths.
7. Load - That which is powered by a voltage source, e.g., a light bulb.

8. Milli - Prefix meaning 1/1000 of the base unit, e.g., milliwatt.
9. Output - That energy, power, voltage, or current which comes out of a device, converter, or system.
10. Photovoltaic Cell (sometimes called Solar Cell) - A device specifically made to convert light energy into electrical energy; light (photo) striking its sensitive surface causes a voltage (voltaic) across its terminals.
11. Photovoltaic Module - A group of photovoltaic cells connected together so as to intercept more light and, therefore, provide more electrical output.
12. Power - Watts or Milliwatts - The rate at which electrical energy is transformed, stored, or used.
13. Radiation - Energy which travels in the form of waves.
14. Resistance - Ohms - A measure of opposition to electrical charge flow.
15. Silicon - A material which is used as the beginning or parent material to make photovoltaic cells, diodes, and other elctrical/electronic devices.
16. Solar Electric Generator System - A system mainly composed of one or more photovoltaic modules, a regulator, one or more storage batteries, and a load.
17. Solar Energy - Energy which comes from the sun.
18. Storage System - One or more rechargeable batteries which store the photovoltaic converter's output in the form of chemical energy.
19. Voltage - Volts - A measure of the "force" which causes electrical charge flow.
20. Wavelength - Micrometers - The length of one complete wave, as in radiation or light energy.

Uses of Photovoltaics

Photovoltaic powered devices can use anywhere from one very small cell to one or more modules, each made up of many very large cells. Obviously, the specific application determines both the size and number of cells involved. Following is a list of devices/uses which involve photovoltaics for electrical power.

1. Light meters - For measuring visible light.
2. Cameras - For controlling shutter speed.
3. Pocket Calculators - For powering the calculator.
4. Light tracking - For following a pattern or line on a blueprint,

or a source of light.

5. Light reflectance measurement - For medical equipment and for determining quality of finishes.
6. Pyronometers - For remote measurement of temperatures of "hot" materials in industries.
7. Space satellites - For providing electrical power for controls and communications.
8. Solar electric generator systems - For:
   a) Powering traffic signal and control equipment in remote areas on both land and sea or lake.
   b) Powering communications repeaters in remote areas.
   c) Providing supplementary electrical power for homes and other buildings,primarily in "sunbelt" regions of the country.

Conditions and Limitations of Photovoltaic Converters

The devices/uses of photovoltaics cited above provide indications regarding some considerations and limitations of applications. Items 1 through 6 do not require sunshine because they can operate from the input of artifical ultraviolet light, visible light, or infrared radiation. For item 7, outer space can provide continuous sunshine. However, the applications under item 8 require sunshine during a considerable portion of the daylight hours. This is necessary to provide sufficient electrical output to power the load and to recharge the batteries of the solar electric generator system.

The applications under item 8 above indicate that the "sunbelt" regions of the country have much greater potential than the more cloudy regions. In all application cases, however, an accurate analysis of available sunshine, the size of the photovoltaic converter needed, and the size of the battery storage system is necesssary toward determining the feasibility of any proposed installation.

While proceeding through the following LAPs bear in mind that the field of photovoltaics has many applications. The principles involved are essentially the same even though the unit used in these LAPs is a solar electric generator system designed primarily for your experimentation.

LEARNING ACTIVITIES

The activiites of this LAP are meant to familiariaze you with the parts which make up the solar electric generator system which you will be using in later LAPs. A sketch of the photovoltaic converter unit controls panel is shown in Figure 1 below. An electrical schematic (symbols drawing) of the entire solar electric generator system is shown in Figure 2 on a following page. If you have had one or more courses in electricity or electronics you might benefit from referring to the schematic of Figure 2 during later LAPs. However, if you haven't had electricity/electronics courses you should still know the functions of the various sections of the controls panel shown in Figure 1. Read on!

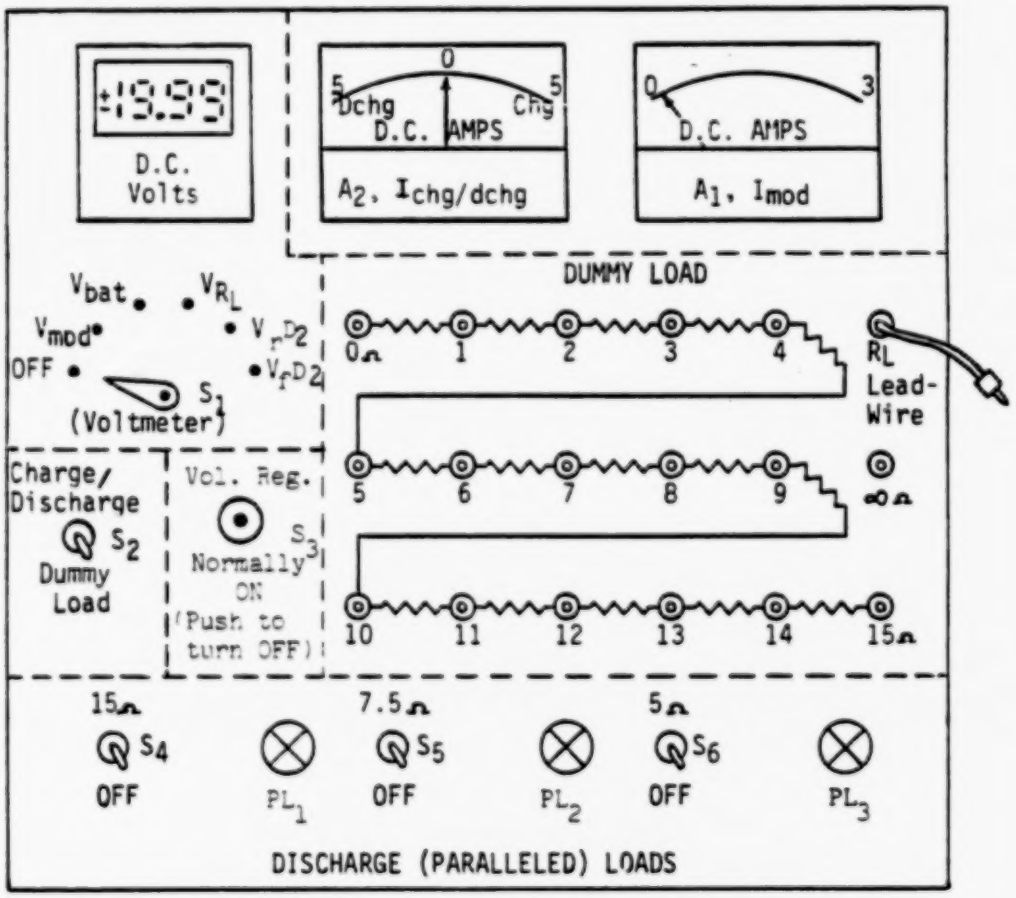

Figure 1. Sketch of Photovoltaic Converter Unit Controls Panel.

For this LAP you are to read the following explanations and be able to locate the controls panel sections in the sketch of Figure 1 and on the solar electric generator system itself.

1. The voltmeter (D.C. Volts) in the upper left-hand corner will display both the polarity and magnitude of voltage being measured. The actual voltage being measured is determined by the position of the voltmeter switch S_1 as follows:
   a) OFF -- No voltage is being measured
   b) V_{mod} -- The photovoltaic module's output voltage is being measured.
   c) V_{bat} -- The storage battery's voltage is being measured.
   d) V_{RL} -- The voltage across any set value of the dummy load resistance R_L is being measured.
   e) $V_r D_2$ -- The reverse voltage across the blocking diode D_2 is being measured.
   f) $V_f D_2$ -- The forward voltage across the blocking diode D_2 is being meausred.
2. The A_1, I_{mod} (D.C. Amps) ammeter in the upper right-hand corner measures the output current of the photovoltaic module. This output current may flow through the dummy load or as a charging current into the battery depending upon the position of switch S_2.
3. The Dummy Load section is made up of a series string of 15 one-ohm resistors. The R_L lead-wire can be connected to any of 17 jacks. These connections can cause R_L to equal 0 ohms which is a short circuit across the module, 1 ohm to 15 ohms to provide 15 values or load resistance, or ∞ ohms which provides an open circuit to the module.
4. When S_2 is in the "Charge or Discharge" position the A_2, $I_{chg/dchg}$ (D.C. Amps) ammeter at the top center of the panel will show the magnitude of current which is charging or discharging the storage battery. Righward needle movement indicates battery charge, and leftward needle movement indicates battery discharge. When the needle is at 0 a balanced condition exists, i.e., the battery is neither charging nor discharging.
5. The Discharge (paralleled) Loads section at the bottom of the panel provides various values of load to the battery by itself or to both the photovoltaic module and the battery. Use of dif-

ferent combinations of S_4, S_5, and S_6 provide the following load resistance values to the battery and/or photovoltaic converter. The three pilot lamps provide visual indication of which of these swithces in ON or OFF.

S_4	S_5	S_6	Resulting Load, Ohms
ON	OFF	OFF	15.0
OFF	ON	OFF	7.50
OFF	OFF	ON	5.00 } same
ON	ON	OFF	5.00 } same
ON	OFF	ON	3.75
OFF	ON	ON	3.00
ON	ON	ON	2.50

6. The voltage regulator switch S_3 has only one function, namely to connect the voltage regulator (see D_1 in Figure 2) into the cicuit when S_3 is ON, or to leave it out of the circuit when OFF. This switch S_3 is a <u>normally closed</u> (ON) pushbutton switch, which enables the voltage regulator diode D_1 to protect the battery from damage from over-charge voltage, which may result from having the photovoltaic module in bright sunshine. This switch can be turned OFF by pressing (sufficiently to cause a "click") and holding the button while making measurements.

The above explanations of various sections on the controls panel are important to remember because they will help you to carry out later LAPs more quickly. They should also aid your understanding of what is happening when making measurements. You may wish to refer back to these LAP #1 explanations later on.

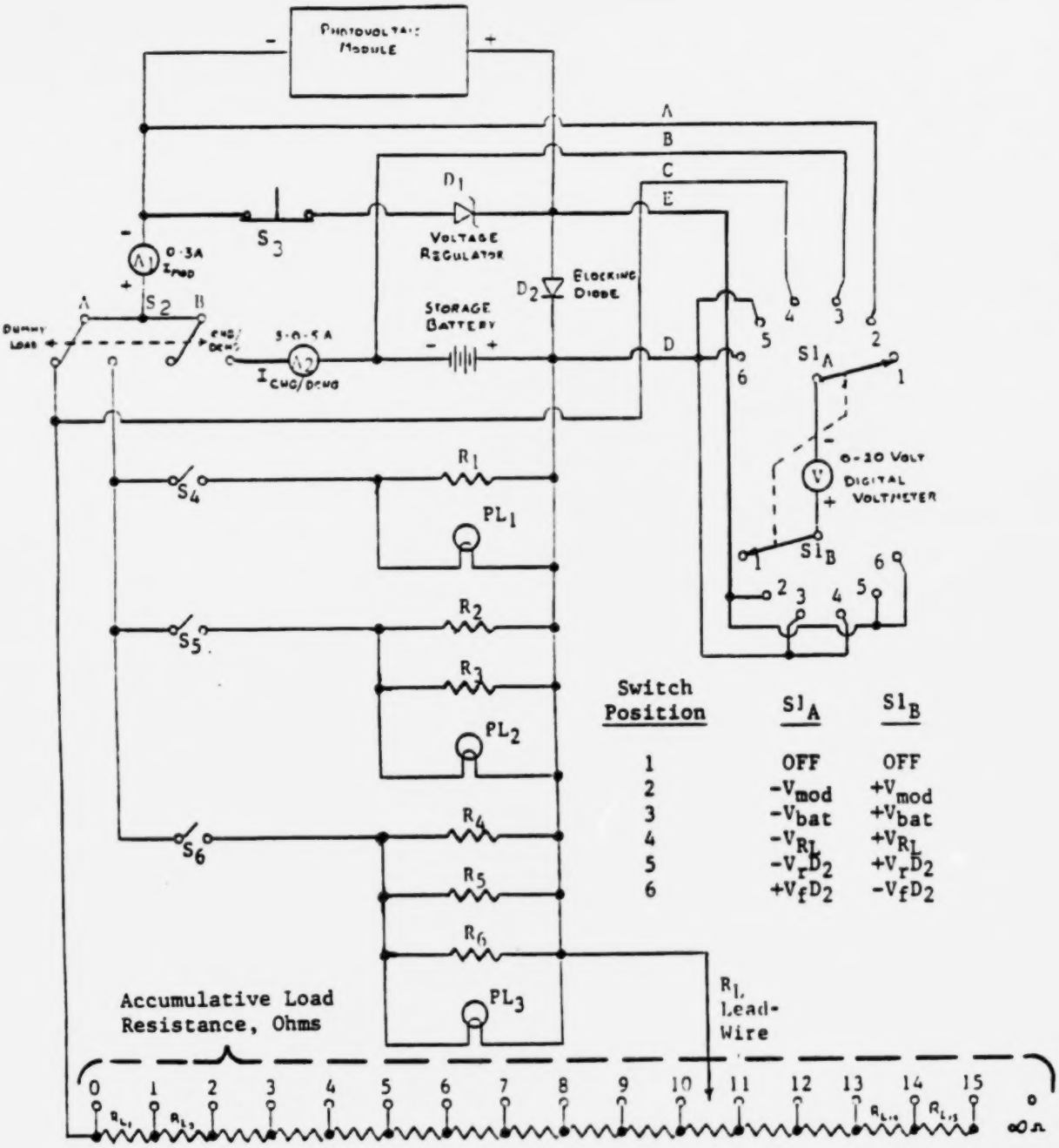

FIGURE 2. Electrical Schematic of Solar Electric Generator.

PARTS SPECIFICATIONS

R_{1-6}	15 Ohm, 25 Watt Resistors
R_{L1-15}	1 Ohm, 10 Watt Resistors
PL_{1-3}	12 Volt (#1891) Pilot Lamps
D_1	14 Volt, 50 Watt (#ECG 5256A) Zener Diode
D_2	6 A, 200 PRV (#ECG 5854) Rectifier Diode
S_1	2 Pole, 6 Position Non-Shorting Rotary Switch
S_2	DPDT 10 Amp Toggle Switch
S_3	Normally Closed 5 Amp Push-button Switch
S_{4-6}	SPST 10 Amp Toggle Switch

Circuit designed by:
Herbert J. Auer, Professor
Dept. of Industrial Technology
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Learning Activity Packet

MAJOR INSTRUCTIONAL UNIT: Photovoltaics

LEARNING ACTIVITY PACKET (LAP) NUMBER: 2

LAP TITLE: Solar Radiation: Input for Photovoltaic Converters

PREREQUISITE LAP (S): 1

LAP PURPOSE: To present background information on the source and nature of the power which may be available as input to a photovoltaic converter.

COMPETENCIES TO BE DEVELOPED:

1. Properly use and read the light intensity detected by an insolation meter.
2. Measure the incident (in-coming) solar insolation under a variety of conditions.
3. Measure the light intensity available from various artificial light sources.

BACKGROUND INFORMATION

Introduction

Solar energy, which comes from the sun, is a non-polluting, ecologically safe, and on-going source of energy. The sun, which is a nuclear power plant, radiates a high amount of energy in all directions into space. The earth's outer atmosphere, which is about 9.3×10^7 miles from the sun, intercepts only about one two-billionth of the radiation emitted by the sun. However, this still amounts to about 1.8×10^{14} kilowatts of power. The various layers of the earth's atmosphere block some shorter wavelengths and reduce the intensity of the longer wavelengths of the radiation coming from the sun.

The radiation which penetrates the atmosphere and is available as input to heat collectors or photovoltaic converters is still quite substantial. On a bright sunny day with the sun directly over head the power reaching the earth's surface is approximately 1000 watts per square meter, which is equivalent to 100 milliwatts per square centimeter. Keep in mind, however, that the intensity is less at latitudes north of the Tropic of Cancer and south of the Tropic of Capricorn because the sun is never directly over head in these regions.

Radiation Spectrum Regions

The total solar radiation spectrum which reaches the earth's surface is composed of three regions. The ultraviolet region consisting of short wavelengths constitutes about 7 percent of the total. The visible light region, or wavelengths from approximately 0.4 to 0.75 micrometers, constitutes about 46 percent of the total. The remaining 47 percent of the total forms the infrared region which is made up of the longer wavelengths, which are felt as radiated heat.

Photovoltaic Converter

A photovoltaic converter is a device which converts light energy into electrical energy. Ideally, such a converter should respond to as much of the total solar radiation as possible, so it can convert the maximum possible input light energy to electrical output energy.

Types of Radiation

The radiation which penetrates the earth's atmosphere is basically of three types. Beam radiation is that which comes directly from the sun, i.e., in parallel rays, without striking any atmospheric particles. Diffused radiation is that which reaches the earth's surface after being scattered and/or reflected by dust particles, moisture in the atmosphere, clouds, etc., which it enocunters. Reflected radiation is that which strikes earth-bound surfaces

and is reflected back from them. On a bright sunny day most of the radiation is of the beam type. However, there will still be some diffused and reflected radiation. On a completely cloudy day no beam radiation penetrates the clouds. Also, only diffused and reflected radiation can exist in the shade of a building, tree, etc., on a sunny day.

Another type of radiation is environmental radiation. This originates from human-made sources such as lights and heated objects. Objects which are hotter than their surroundings will radiate primarily infrared wavelengths. Lights, however, may radiate wavelengths in the ultraviolet, visible, infrared, or a combination of regions of the total spectrum depending on the purpose for which the light was made.

Insolation Meter

Insolation is defined as the amount of solar radiation striking unit area of a surface. This total may be composed of beam, diffused, and reflected radiation. An insolation meter is one instrument used to measure this total radiation. The insolation meter, to be used in this and later Learning Activity Packets, has three scales as follows:

1. BTU-hr/ft^2 --- English system units used for working with solar heat collectors.
2. Langleys/hr = Calories-hr/cm^2 --- Metric system units used for working with solar heat collectors.
3. mW/cm^2 --- Metric system units used for working with photovoltaic converters.

LEARNING ACTIVITIES

The following activites are provided to familiarize you with the insolation meter and its proper use in measurement of radiation originating from various sources. The insolation meter is a delicate instrument. Therefore, handle it carefully and never hold it so near any radiation or light source that the needle goes off scale or that couses the sensor or meter enclosure to become warm.

1. Obtain the insolation meter and examine it carefully, Then answer the following questions.
   a. What is the full-scale value and what units are used for the top meter scale? _____
   b. For what type of work is the top scale appropriate? _____
   _____
   c. What is the full-scale value and what units are used for the center meter scale? _____
   d. For what type of work is the center scale appropriate? ____
   _____
   e. What is the full-scale value and what units are used for the bottom meter scale? _____
   f. For what type of work is the bottom scale appropriate? ____
   _____
2. If possible, carefully move the insolation meter so its sensor approaches an incandescent lamp (ordinary light bulb).
   a. Did the meter needle move? _____ How much? _____
   b. What region(s) of the radiation spectrum are involved in an incandescant lamp's radiation? _____
   _____
3. If possible, carefully move the insolation meter so its sensor approaches a fluorescent lamp.
   a. Did the meter needle move? _____ How much? _____
   b. What region(s) of the radiation spectrum are involved in a fluorescent lamp's radiation? _____
   _____

NOTE: Depending on sky conditions, do either or both 4 and 5 below.

4. If it is a sunny day, take the insolation meter outdoors and:
   a. Measure and record (_____) the insolation, applicable to photovoltaics, having the sensor perpendicular to

the sun's rays.

b. What type(s) of radiation are involved in this measurement? _____

_____

c. Measure and record (_____) the insolation, applicable to photovoltaics, having the sensor in a horizontal plane in the shade of a building or tree.

d. What type(s) of radiation are involved in this measurement? _____

_____

5. If it is a cloudy day, take the insolation meter outdoors and:

a. Measure and record (_____) the insolation, applicable to photovoltaics, having the sensor in the direction which produces maximum needle deflection.

b. What type(s) of radiation are involved in this measurement? _____

_____

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Learning Activity Packet

MAJOR INSTRUCTIONAL UNIT: Photovoltaics

LEARNING ACTIVITY PACKET (LAP) NUMBER: 3

LAP TITLE: Photovoltaic Cells

PREREQUISITE LAP (S): 1 and 2

LAP PURPOSE: To provide background information regarding the make-up of photovoltaic cells, how they function, their ratings, and how their basic characteristics can be measured.

COMPETENCIES TO BE DEVELOPED:

1. Measure/determine the input area of one cell and of the entire photovoltaic module.
2. Measure/determine the insolation and total input light intensity received by the photovoltaic module.
3. Measure/determine the short-circuit current and the open-circuit voltage per cell outputted by the photovoltaic module.

BACKGROUND INFORMATION

Cell Structure

Most all photovoltaic (solar) cells of today are made using silicon as the base or parent material. A very thin circular wafer is cut from an N-type silicon ingot, which forms the basic structure of the cell. The original ingot is made N-type by doping (adding a very small quantity) the silicon parent material with phosphorous. The silicon has four valence electrons and the phosphorous has five valence electrons. Thus, there exists an imbalance (an excess) of electrons between adjacent atoms of the N-type (negative material (see Figure 1).

One surface of this N-type wafer is then doped, by a diffusion process, with boron. The boron has three valence electrons, and this causes an imbalance (a deficiency of electrons, or holes) between adjacent atoms. Thus, the boron diffused surface is called P-type (positive) material. (see Figure 1).

The P-N Junction

When N-type and P-type silicon are brought against each other a P-N junction is formed (see Figure 2). This results in both diode and photovoltaic characteristics. A typical P-N diode will easily conduct electron flow from the N- to the P-type region. Thus, a photovoltaic cell should never by connected with the N-type to the negative and P-type to the positive terminals of any electrical power source unless additional protective component(s) are provided.

The photovoltaic characteristics (see Figure 2) result when photons of light are allowed to strike the thin diffused surface of P-type silicon. Each photon of light which penetrates to near the P-N junction can cause release of one electron-hole pair. This results in a build-up of freed electrons and holes form an electric field which causes the output terminal polarity shown in Figure 2.

The Pick-Up Grid

In order to have useful electrical output, there must be a means of "picking up" the electrical charges from the N- and P-type silicon and delivering them to an external load. This is accomplished by covering the N-type surface with a metal foil. However, the P-type surface must be accessible to the incident light. Therefore, contact to this surface is made by attaching a grid of metal conductors (flat wires) to the P-type silicon. This pick-up gird must be widely distributed over the surface and provide sufficient

current carrying capacity, while at the same time covering minimum area so as not to substantially reduce the area which light can strike.

Cell Ratings

Two basic specifications or ratings are applicable to all photovoltaic cells. These are as follows:

1. The output voltage V_o of a cell is determined primarily by the material from which the cell is made, typically silicon. Maximum voltage is obtained when the output is open circuited, i.e., infinite load resistance (only a voltmeter) is connected across the output. This is labeled V_{oc}/cell. For series-connected cells one can measure the total open-circuit output voltage of the series string, and then V_{oc}/cell = total V_{oc}/Number of Cells connected in series.
2. The output current I_o of a cell will depend upon a) the material from which the cell is made, b) the area A of the cell (measured in cm^2 units), and c) the actual insolation, or light intensity, I_a (measured in mW/cm^2 units) which strikes the cell. Maximum current is obtained when the output is short-circuited, i.e., zero load resistance (only the ammeter) is connected across the output. This is labelled I_{sc}. All series-connected cells have the same current flow. However, if the cells are connected in parallel (see Figure 4) the I_{sc}/cell = Total I_{sc}/Number of Cells connected in parallel.

   Another method of indicating the I_{sc} value is by output current per square centimeter. This can be obtained by $I_{sc}/cm^2 = I_{sc}/A$. Because different converters may have different sized cells, this method provides a means of comparing I_{sc} values while disregarding cell size.

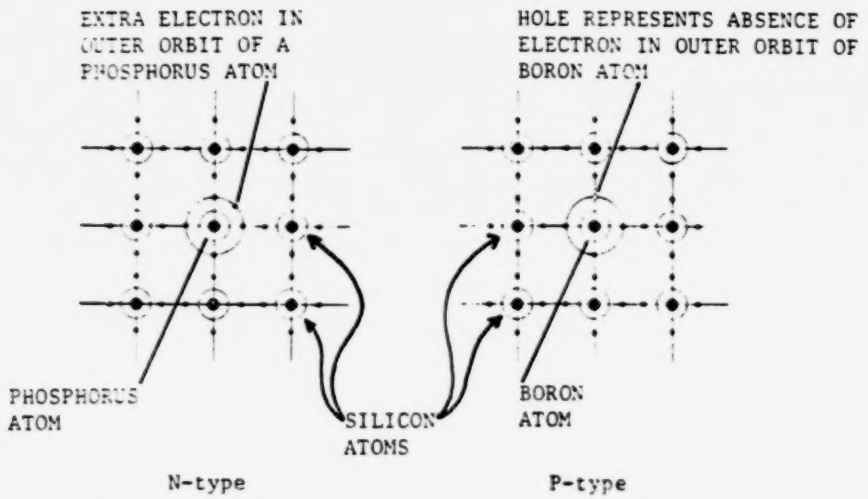

EXTRA ELECTRON IN OUTER ORBIT OF A PHOSPHORUS ATOM
HOLE REPRESENTS ABSENCE OF ELECTRON IN OUTER ORBIT OF BORON ATOM
PHOSPHORUS ATOM
SILICON ATOMS
BORON ATOM
N-type
P-type

FIGURE 1. Illustration of Free Electrons in N-type and Free Holes in P-type Silicon due to Doping.

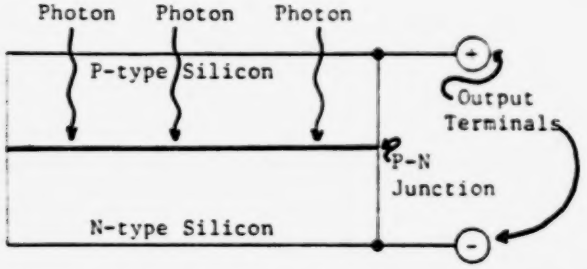


FIGURE 2. Illustration of Photons of Light Penetrating P-type Silicon to near P-N Junction, and Resulting Output Terminal Polarity.

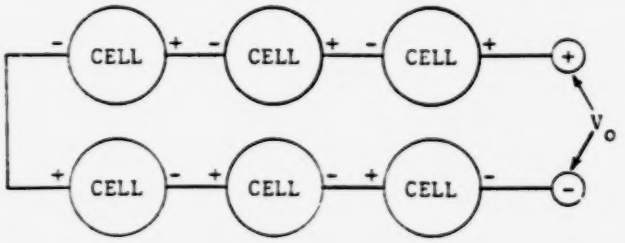


FIGURE 3. Series Connection of Cells produces Additive Output Voltage.

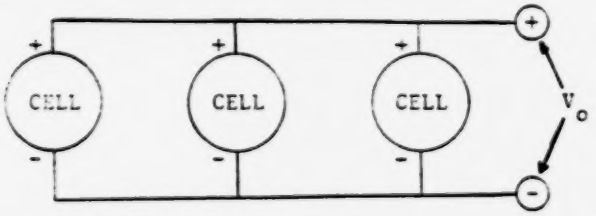
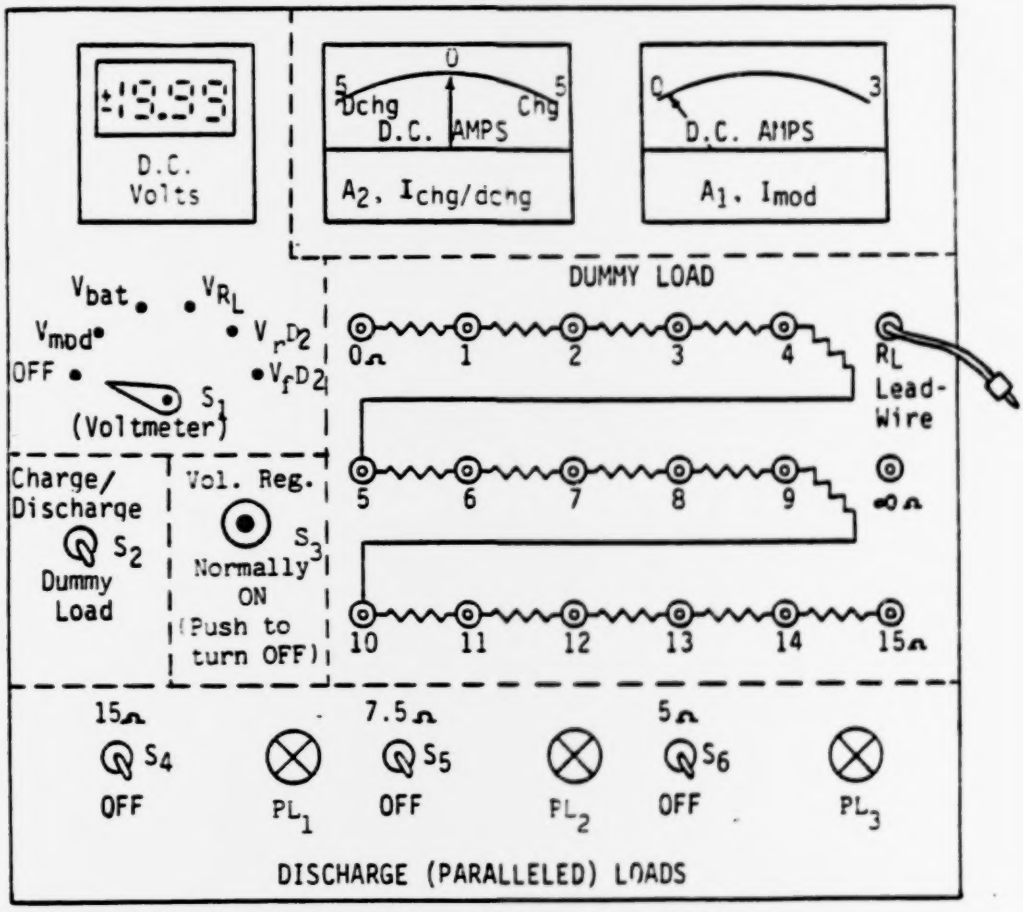


FIGURE 4. Parallel Connection of Cells Produces Additive Output Current Capability.

LEARNING ACTIVITIES
(MUST BE DONE ON A SUNNY DAY)

The following activites are provided to acquaint you with basic measurements regarding the photovoltaic converter and the characteristics or ratings of the solar cells contained in the photovoltaic module. An outline sketch of the photovoltaic converter unit control panel is shown below.



Photovoltaic Converter Unit Controls Panel

Beginning Positions

S1 OFF, S2 Dummy Load, S3 ON, S4 OFF

S5 OFF, S6 OFF, R_L leadwire ∞ ohms

1. Carefully move the solar electric generator system outdoors onto a level surface. Orient it, be rotating the cart, so that the converter is toward the sun. This position is achieved when the converter's shadow is centered on the width of the cart's top surface.

2. Position all six switches and the R_L leadwire to the beginning positions immediately below the sketch.
3. Using a metric ruler, measure and record (____ cm)the diameter of one of the photovoltaic cells of the module.
4. Using the formula $A=\pi r^2$ calculate and record (____ cm^2) the area of one of the photovoltaic cells of the module.
5. Observe the interconnection of the cells of the module and record (_____) whether they are connected in series, parallel, or otherwise.
6. Count and record (____) the total number of cells in the photovoltaic converter module.
7. Obtain the insolation meter, place it flat on the surface of the converter, and read and record (_____mW/cm^2) the insolation I_a which strikes the converter's cells.
8. Turn switch S1 to $V_{mod.}$ and while pressing S_3 to turn it OFF accurately read the voltmeter and record (____ volts) the total open-circuit output voltage V_{oc} of the module. Notice that for this measurement the R_L leadwire is at infinite ohms.
9. Move the R_L leadwire to 0 ohms of the dummy load and while pressing S_3 to turn it OFF accurately read the I_{mod} ammeter and record (____ amps) the short-circuit output current I_{sc} of the module.
10. Using the information recorded in 4 through 9 above show your work for calculating:
    a) the V_{oc} per cell;
    b) the I_{sc} per cell, and
    c) the I_{sc} per cm^2 for this photovoltaic converter.
11. Briefly describe how the answers of 10 above would be different if the insolation I_a of 7 above were substantially lower than that measured.

    _____

    _____

    _____
12. Return all switches and the R_L leadwire to the positions specified below the sketch. Then return the solar electric generator system to its original location.

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Learning Activity Packet

MAJOR INSTRUCTIONAL UNIT: Photovoltaics

LEARNING ACTIVITY PACKET (LAP) NUMBER: 4

LAP TITLE: Solar Electric Generator System, Part A

PREREQUISITE LAP (S): 1 and 2

LAP PURPOSE: To provide information regarding several parts of a solar electric generator system and the functioning of those parts within the system.

COMPETENCIES TO BE DEVELOPED:

1. Measure and determine the effects which cell area has on photovltaic output current and voltage.
2. Measure and determine the effects which one faulty cell may have on the photovoltaic module's output current and voltage.
3. Measure the voltage appearing across the blocking diode under certain conditions.

BACKGROUND INFORMATION

The Solar Electric Generator System

Solar electric generator systems typically consist of several sub-parts, each having a specific function within the total system. A simplified electrical schematic of a complete solar electric generator system is shown in Figure 1. The five parts of the system are a) the solar array, b) the blocking diode, c) the voltage regulator, d) the storage battery, and e) the load. Only a) and b) of the five parts will be covered in this Learning Activity Packet (LAP). The functions of the other parts will be covered in later LAPs.

Photovoltaic Cell, Module, and Array

The characteristics of the silicon photovoltaic cell were explained and measured/determined in LAP #3. Also within LAP #3 you were asked to count and record the total number of cells in the photovoltaic module. This wording indicates that a photovoltaic module is composed of a group of series connected cells. Thus, the photovoltaic converter (converts light energy into electrical energy) which you have been using is a module. All photovoltaic modules are designed to deliver a certain value of current at a certain level of voltage, such as the voltage needed to charge the typical 12 volt lead-acid storage battery.

Many practical applications for solar electric generator systems require higher levels of current and/or voltage than one module can deliver. For these applications two or more modules can be interconnected in series and/or parallel to provide the needed level of current and voltage. When this is done the interconnected modules are referred to as a photovoltaic or solar electric array. The modules of an array must produce equal voltages when connected in parallel and equal currents when connected in series.

An illustration of an array made up of six modules is sketched in Figure 2. The interconnection of modules produces the same results as the interconnection of individual cells. In a series connection the voltages are additive. In a parallel connection the current delivery capabilities are additive.

The Blocking Diode

The function of the blocking diode (see Figure 1) is to protect the solar electric module, or array, when the light stricking the module does not produce sufficient voltage to provide charge to the storage battery. This condition

always occurs during night-time, and may occur during cloudy days. Since electron flow readily occurs from the cathode (bar of diode symbol) to the anode (arrow of diode symbol) but not in the opposite direction, the battery could discharge through the array during cloudy or night-time hours. By placing the blocking diode in the circuit in opposite polarity to that of the array, the battery cannot discharge through the array. The polarities of the array-equivalent and blocking diodes are shown in Figure 1. The blocking diode "blocks" battery discharge because electron flow will not occur when the anode (arrow) is more negative than the cathode (bar). As a result, nearly all of the battery voltage V_b appears as a reverse or negative voltage across the blocking diode. This diode reverse voltage is symbolized V_r.

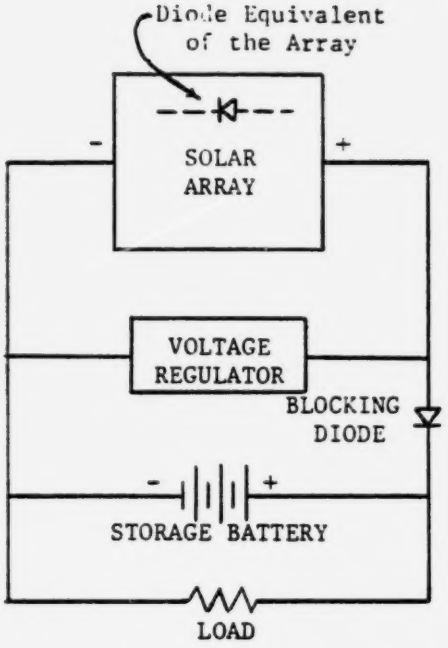

FIGURE 1. Electrical Schematic of a Complete Solar Electric Generator System.

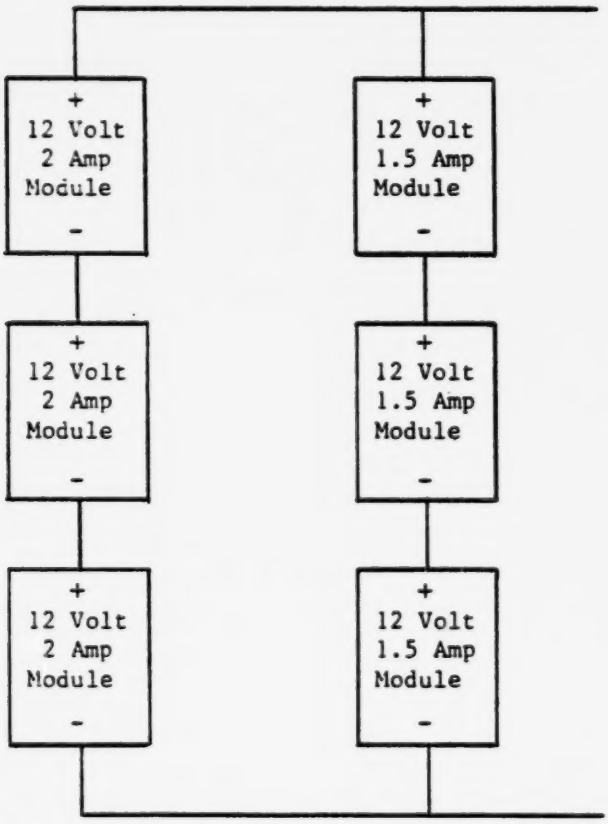

FIGURE 2. An Array of Interconnected Modules.

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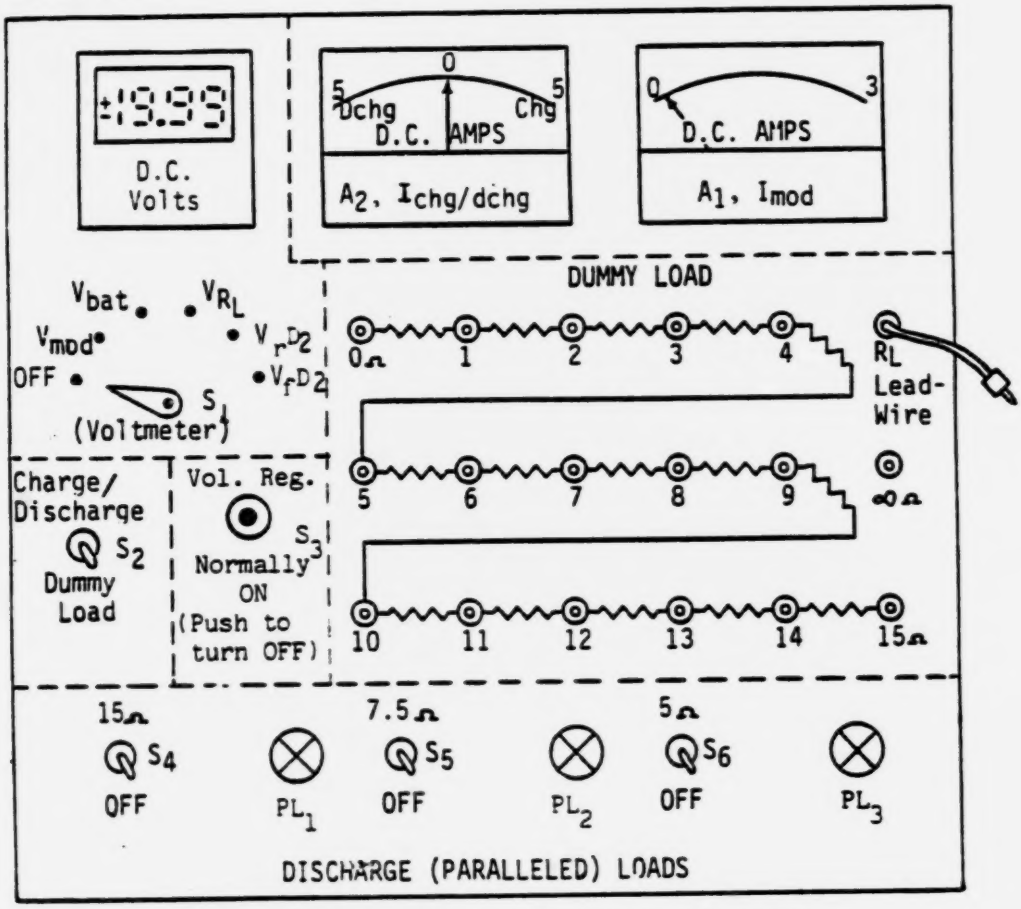
LEARNING ACTIVITIES
(MUST BE DONE ON A SUNNY DAY)

The following activities will acquaint you with the significance of the series connection of cells within the photovoltaic module, what happens when one or more cells are covered so they cannot receive light, and why it is necessary to have the blocking diode D_2 in the solar electric generator system. An outline sketch of the photovoltaic converter unit controls panel is shown below.



Photovoltaic Converter Unit Controls Panel
Beginning Positions

S_1 OFF, S_2 Dummy Load, S_3 ON, S_4 OFF,

S_5 OFF, S_6 OFF, R_L lead-wire ∞ ohms

1. Carefully move the solar electric generator system outdoors onto a level surface. Orient it, by rotating the cart, so that the converter is toward the sun. This position is achieved when the converter's shadow is centered on the width of the cart's top surface.
2. Position all six switches and the R_L leadwire to the beginning positions immediately below the sketch.
3. Connect the R_L Lead Wire to the 7-ohms jack. This will provide a suitable load resistance for the remaining parts of this LAP.
4. Set the Voltmeter switch S_1 to the V_{mod} position.
5. Measure and record V_{mod} = _____volts and I_{mod} = _____ amps. The module's output power $P_o = V_{mod} \times I_{mod}$. Calculate and record this power. P_o = _____ watts.
6. Set the Voltmeter switch S_1 to the V_{RL} position.
7. Measure and record V_{RL} = _____volts and I_{mod} = _____ amps. The power actually delivered to the load is $P_{RL} = V_{RL} \times I_{mod}$. Calculate and record this power. P_{RL} = _____watts.
8. Set the Voltmeter switch to the V_fD_2 position.
9. Measure and record the blocking diode's forward voltage V_fD_2 = _____volt and I_{mod} = _____amps. The power which is lost in the blocking diode is $P_{D2} = V_fD_2 \times I_{mod}$. Calculate and record this power. P_{D2} = _____watt(s).
10. The module's output power should equal the power delivered to the load plus the power lost in the blocking diode, $P_o = P_{RL} + P_{D2}$. Add the P_{RL} of #7 to the P_{D2} of #9. Then check to see if this sum is close to the P_o value recorded in #5.
11. Set the Voltmeter switch S_1 to the V_{mod} position.
12. Now, using the single cell cover (circular piece of masonite) from the cart drawer, cover any one of the module's cells without shading any others and read and record what happened to V_{mod} and to I_{mod}. _____
_____
13. Now, using the masonite strips from the cart drawer, cover one complete vertical column of cells, such as those on the left-hand side of the module. Read and record what happened to V_{mod} and to I_{mod}. _____
_____

14. Cover the entire module with the opaque (masonite) shield so no light can strike the module. This simulates a night-time condition. Set S_2 to the charge/discharge position, and then:
    a) Read and record V_{mod} = _____volt(s) and I_{mod} = _____amps.
    b) Set the Voltmeter switch S_1 to the V_{bat} position, and read and record V_{bat} = _____volts.
    c) Set the Voltmeter switch to the V_rD_2 position, and read and record the blocking diode's reverse voltage V_rD_2 = _____volts.
15. Using the information from #14 above, briefly discuss the reason for having the blocking diode in the circuit. _____

    _____

    _____

    _____
16. Return all swtiches and the R_L leadwire to the positions specified below the sketch. Then return the solar electric generator system to its original location.

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Learning Activity Packet

MAJOR INSTRUCTIONAL UNIT: Photovoltaics

LEARNING ACTIVITY PACKET (LAP) NUMBER: 5

LAP TITLE: Solar Electric Generator System, Part B

PREREQUISITE LAP (S): 1, 2 and 4

LAP PURPOSE: To provide information regarding several parts of a solar electric generator system and the functioning of those parts within the system.

COMPETENCIES TO BE DEVELOPED:

1. Measure and determine the effects on the photovoltaic converter's output voltage both with and without the voltage regulator in the circuit.
2. Measure and determine the effects which the voltage regulator has on the battery's voltage.

BACKGROUND INFORMATION

The Solar Electric Generator System

In Learning Activity Packet (LAP) #4 the complete solar electric generator system was described as consisting of five parts. The electrical schematic of the system is repeated here in Figure 1. The parts of the system to be given coverage in this LAP are the voltage regulator and the storage battery. The fifth part, the load, will be covered in several later LAPs.

Voltage Regulator

As shown in Figure 1, the voltage regulator is connected directly across the solar array, or solar module. The function of the voltage regulator is to protect the battery from over-charge. In an automobile the voltage regulator acts to "shut down" the charging source, i.e., the alternator, when the battery voltage reaches a certain level. For a solar electric generator system the charging source is the sun, which obviously cannot be shut down. Therefore, the voltage regulator in a solar electric generator system acts as a bypass path for the module or array current when the battery voltage reaches a certain level.

The voltage regulator used in a solar electric generator system can be specially designed like that shown in Figure 2 wherein the bypass path is through the silicon power transistor and the wire-wound power resistor. Another less expensive but less accurate type of regulator, shown in Figure 3, is in the solar electric generator system you have been using. In this circuit the byspass path is through the zener diode. This zener diode conducts electron flow, from anode (arrow) to cathode (bar), when the voltage across it reaches its designed zener voltage V_z.

Storage Battery

The type of storage battery, or batteries, used in a solar electric generatory system depends upon many factors such as the temperatures which they must withstand, the desired energy storage density (watt-hours per cubic foot), and the anticipated "depth" of charge-discharge cycle. For some applications nickel-cadmium batteries are best, while for others the lead-acid battery is appropriate. One lead-acid storage battery is provided with the solar electric generator system you have been using.

The typically referred to 12-volt lead-acid battery consists of six series-connected cells. When fully charged (but not connected to a charger or

a load) each cell of this lead-acid battery should furnish about 2.2 volts. Thus, the battery's full-charge voltage should be about 6 x 2.2 volts = 13.2 volts. In order to charge this battery the charging source must produce a voltage greater than the battery voltage. Keep in mind, however, that as soon as a charging source is connected across the battery, the charger voltage (the photovoltaic module voltage V_{mod}) and the battery voltage V_{bat} become the same in magnitude, except for the small voltage drops across the ammeters used in this solar electric generator system. Also, as the battery's charge-level increases, both V_{mod} and V_{bat} will increase slightly.

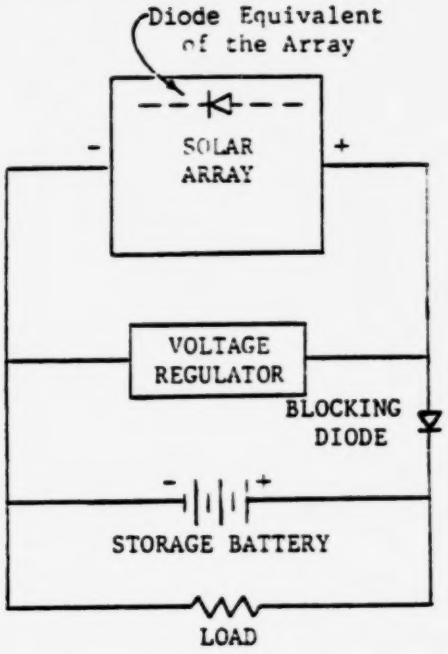

FIGURE 1. Electrical Schematic of a Complete Solar Electric Generator System.

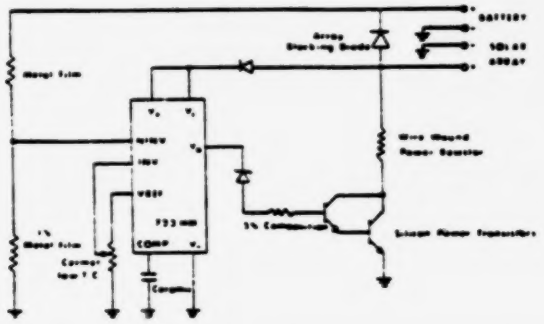

FIGURE 2. Typical Basic Voltage Regulator Circuit.

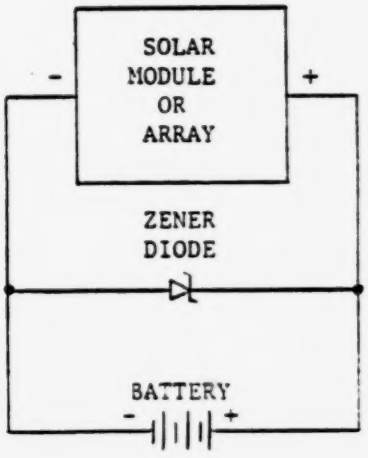

FIGURE 3. Simple Zener-Diode Voltage Regulator Circuit.

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LEARNING ACTIVITIES
(MUST BE DONE ON A SUNNY DAY)

The following activities will show how the voltage regulator can effect the output voltage of the photovoltaic converter. To show this we will connect a high dummy load resistance to the converter. Also, these activities will attempt to show how the voltage regulator protects the battery from overcharge. Succeeding in this attempt may require some time because the battery's no-load voltage with S_3 OFF must exceed the zener voltage V_z of diode D_1 in order for the "protective action" of the regulator to be measurable when S_3 is turned ON by pressing the button.

The outline sketch of the photovoltaic converter controls panel will not be shown in this or following LAPs. You may refer back to Figure 1 of LAP #1 for this sketch, or you may wish to view the entire system's schematic in Figure 2 of LAP #1.

1. Carefully move the solar electric generator system outdoors onto a level surface. Orient it, be rotated the cart, so that the converter is toward the sun. This position is achieved when the converter's shadow is centered on the width of the cart's top surface.
2. Place all six switches and the R_L leadwire in the following positions: S_1 -- OFF, S_2 -- Dummy Load, S_3 -- ON, S_4 through S_6 -- OFF, and R_L leadwire -- ∞ ohms.
3. Connect the R_L leadwire to the 15 ohm jack and then turn the voltmeter switch S_1 to the V_{mod} position
4. Read and record the module's output voltage V_o = _____volts and the output current I_o = _____amps, while pressing and holding S_3 OFF.
5. Allow S_3 to turn ON, i.e., don't press it. This permits the regulator to limit the output voltage. Read the record the module's output voltage. V_o = _____ volts and output current I_o = _____ amps.
6. Briefly discuss how the two voltages and the two currents of steps 4 and 5 differed and why. _____

   _____

   _____

   _____ _____
7. Return all six switches and R_L leadwire to the positions given in step 2 above.
8. Turn the voltmeter switch S_1 to the V_{mod} position. Then, while pressing and holding S_3 OFF, read and record the module's output voltage

V_o = _____ volts. This is actually V_{oc} because R_L is at infinite ohms.

9. Allow S_3 to turn ON, i.e., don't press it. Read and record the module's output voltage V_o = _____ volts. This is actually the zener regulator's voltage V_z because the zener regulator is the only path through which the module's output current can flow.
10. Turn the voltmeter switch S_1 to the V_{bat} position. While pressing S_3 OFF, measure and record the no-load battery voltage. V_{bat} = _____ volts.
11. Turn S_2 to the Charge/Discharge position and allow the converter to charge the battery for a considerable time.
12. After this considerable charging time read and record the battery's charging voltage as $V_{bat\ charging}$ = _____ volts.
13. Now turn the voltage regulator switch OFF by pressing S_3. Read and record V_{bat} = ____ volts. This represents the maximum voltage to which the zener voltage regulator will permit the battery to charge.
14. Briefly discuss why the voltages of steps 8 and 9 above where different.

_____

_____

_____

_____

15. Briefly discuss why the voltages of steps 12 and 13 above were different.

_____

_____

_____

_____

16. Place all six switches and the R_L leadwire to the positions given in step 2 above. Then return the solar electric generator system to its original location.

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Learning Activity Packet

MAJOR INSTRUCTIONAL UNIT: Photovoltaics

LEARNING ACTIVITY PACKET (LAP) NUMBER: 6

LAP TITLE: Characteristics of Silicon Cells

PREREQUISITE LAP (S): 1 & 2

LAP PURPOSE: To provide information regarding the effects which light source conditions have on the output response of a silicon-cell photovoltaic converter.

COMPETENCIES TO BE DEVELOPED:

1. Measure and determine the effects which ultraviolet input-light blockage has on the voltage and current outputs of a silicon-cell photovoltaic converter.
2. Measure and determine the effects which beam radiation input blockage has on the voltage and current outputs of a silicon-cell photovoltaic converter.

BACKGROUND INFORMATION

Solar Radiation Spectrum

The wavelength spectrum of radiation which can reach the earth's surface on a bright sunny day is composed of three regions, as shown in Figure 1. This graph indicates the distribution of the total available energy, with 7% being in the ultraviolet, 46% in the visible light, and 47% in the infrared region of the total spectrum. A knowledge of this distribution is helpful when studying and using any photovoltaic converter. Ideally, a solar electric generator system should be capable of responding to or using as much as possible of this total spectrum as input energy.

Silicon Cells' Spectrum Response

At present silicon cells are the most-used type of converter for solar electric systems. One important reason for this is that silicon cells respond to a fairly wide region of the total available solar radiation which reaches the earth's surface. Figure 2 shows the wavelength response of the silicon cell. This graph shows that the silicon cell's output is maximum (100% of that possible) at a wavelength of about 0.875 micrometer. By comparing this wavelength with the graph of Figure 1 we observe that this maximum output occurs near the boundary of the visible light and infrared regions.

Further comparison of the curves graphed in Figures1 and 2 shows that the silicon cell's response decreases to near zero at the shorter wavelength end of the visible light region. At the longer wavelengths, the silicon cell's output nears zero at about 1.15 micrometers (Figure 2), which is near the center of the 46% infrared range area (Figure 1). Thus, we see that silicon cells can respond to a fairly large portion of the solar radiation reaching the earth.

Research is currently being conducted by scientists and industries toward development of more effective photovoltaic converter materials. A variety of materials show good promise in this regard. However, until the newer materials can be proven effective and mass produced at a competitive cost, silicon cells will continue to be dominant in the photovoltaic converter field.

Other Response Factors

Several other factors can act toward determining the output of a silicon

photovoltaic converter, or solar electric generator system. Some of these will be explained here.

On a bright sunny day the insolation on the cells of the converter will be primarily beam radiation and consist of the full spectrum of solar radiation (see Figure 1). However, during a cloudy day this insolation may be reduced to a much lower level, and will be primarily diffused radiation. Comparison of the available solar radiation on a sunny day and a cloudy day can be made by viewing the two curves graphed in Figure 3.

The time of day also affects the level of available insolation. Both curves in Figure 3 show this fact, though the amount of change throughout the day is greater for the sunny day. Also, it can be seen that both curves reach maximum at mid-day.

Another factor affecting available insolation is the time of year. In the Northern hemisphere the available insolation is highest during the summer and lower during the winter months. This throughout-the-year change in insolation is due tc the changing altitude angle (angular height above horizontal) of the sun.

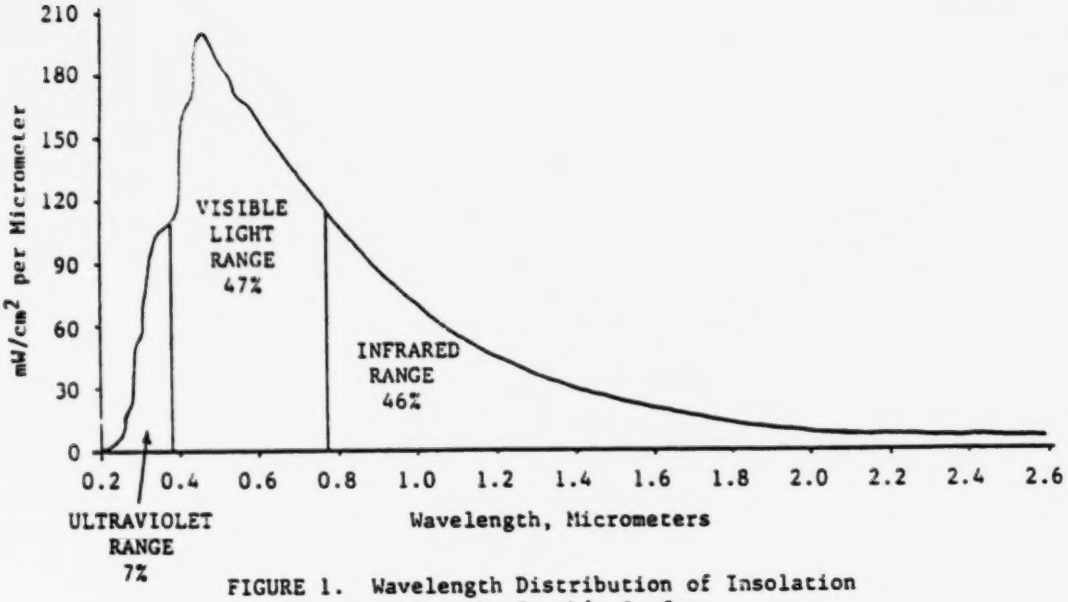

FIGURE 1. Wavelength Distribution of Insolation Reaching the Earth's Surface.

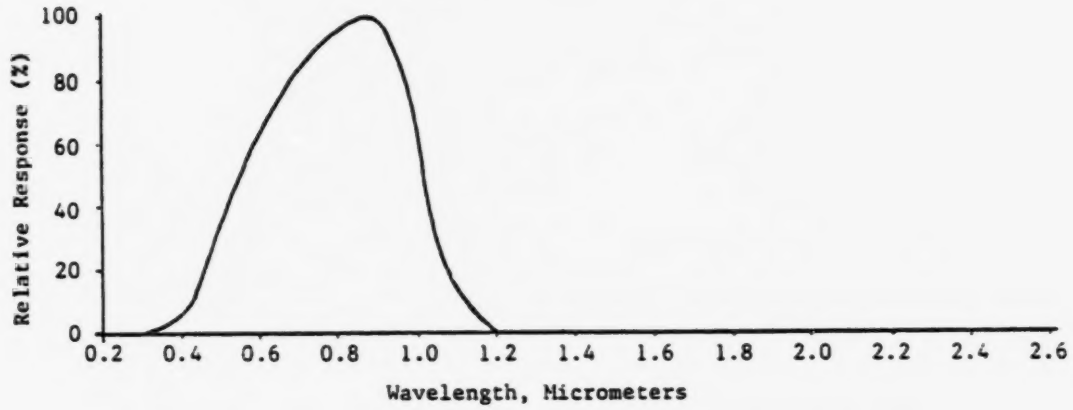

FIGURE 2. Wavelength Response of Silicon Photovoltaic Cell.

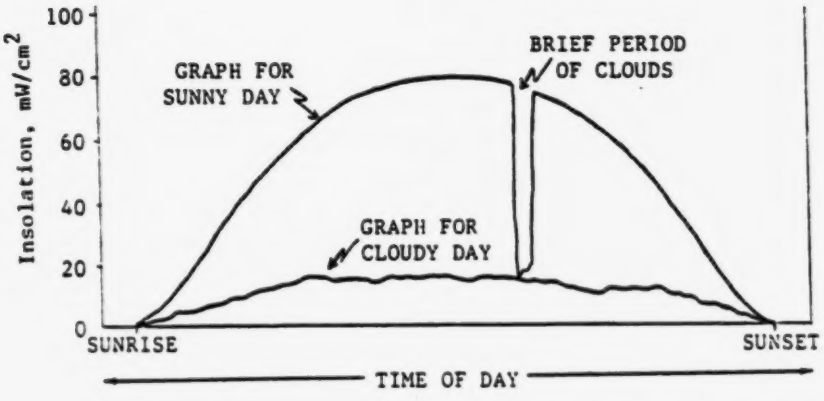

FIGURE 3. Available Insolation Curves for a Cloudy and a Sunny Day.

LEARNING ACTIVITIES
(MUST BE DONE ON A SUNNY DAY)

The following activities will show, to a limited extent, the effects which conditions lacking full spectrum radiation and lacking beam radiation have on the output voltage and current of a silicon-cell photovoltaic converter. We will use the full spectrum beam radiation input condition as a reference by which to judge the other conditions.

1. Carefully move the solar electric generator system outdoors onto a level surface. Orient it, be rotating the cart, so that the converter is toward the sun. This position is achieved when the converter's shadow is centered on the width of the cart's top surface.
2. Place all six switches and the R_L leadwire in the following positions:

   S_1 -- OFF, S_2 -- Dummy Load, S_3 -- ON, S_4 through S_6 -- OFF, and R_L leadwire -- ∞ ohms.
3. Turn the voltmeter switch S_1 to the V_{mod} position and connect the R_L leadwire to the 7-ohms jack. This will provide a suitable load resistance for the remaining parts of this LAP.
4. Read and record the module's output voltage V_o = _____volts and the output current I_o = _____amps. Calculate the output power by $P_o = V_o \times I_o$ = _____watts. <u>These three values will serve as the references for later measurements</u>.
5. Now cover the module with the translucent <u>shield</u>. This shield acts somewhat like ordinary window glass, which blocks most of the ultraviolet radiation region of the radiation coming from the sun.
6. Read and record the module's output voltage V_o = _____volts and output current I_o = _____amps. Calculate the output power by $P_o = V_o \times I_o$ = _____watts.
7. Briefly describe what change(s) occurred in the voltage, current, and power levels of step 6 compared to those of step 4 and why.

   _____

   _____

   _____
8. Remove the translucent shield from the module.
9. Now rotate the cart with solar electric generator system about 180 degrees, so that the sun is to the back of the converter. Also be

certain there is no direct reflection of sun rays onto the module's front surface from a building or other object. Under these conditions no beam radiation will strike the module's cells, but a considerable amount of diffuse radiation should still be available.

10. Read and record the module's output voltage V_o = _____volts and output current I_o = _____amps. Calculate the output power by $P_o = V_o \times I_o$ = _____watts.
11. Briefly describe what change(s) occurred in the voltage, current, and power levels of step 10 compared to those of step 4 and why.

    _____

    _____

    _____
12. Place all six switches and the R_L leadwire to the positions given in step 2 above. Then return the solar electric generator system to its original location.

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Learning Activity Packet

MAJOR INSTRUCTIONAL UNIT: Photovoltaics

LEARNING ACTIVITY PACKET (LAP) NUMBER: 7

LAP TITLE: PHotovoltaic Module Source Resistance

PREREQUISITE LAP (S): 1 and 2

LAP PURPOSE: To provide information on and experience in determining the internal resistance of a photovoltaic converter and how this can effect the converter's output.

COMPETENCIES TO BE DEVELOPED:

1. Measure and determine the photovoltaic converter's output and internal resistance with full insolation of input.
2. Measure and determine the photovoltaic converter's output and internal resistance when various restrictions of insolation are present.

BACKGROUND INFORMATION

Internal Resistance

All electrical sources, whether an engine-driven generator, a battery, or a photovoltaic converter, have some internal resistance. This resistance is inside the source itself, and is symbolized R_i.

By way of example, the 12-volt lead-acid battery will deliver considerable cranking power to the starter of an automobile engine when the battery is warm and fully charged. This is because its internal resistance is very low under these conditions. Thus, its internal voltage drop, or loss, is low and it can provide a higher voltage to cause a higher current flow to the starter. If that battery is discharged and cold, however, its R_i will be higher and it may not provide enough power to the starter. In effect, too much of the battery's power is lost internal to the battery and too little is available for the starter.

Figure 1 shows a schematic symbol representation of a voltage source V_s having internal resistance R_i. Notice that both V_s and R_i are drawn internal to the source. An adjustable load resistance R_L is connected to the source's output terminals. The source's output voltage V_o appears across the load. The solid arrow through the R_L symbol indicates that we can manually adjust this resistance. However, the dashed arrow through the R_i symbol indicates that its resistance is not manually adjustable. It can vary because it is dependent upon specific conditions, somewhat like the temperature and charge level of the lead-acid battery described above.

Maximum Power Transfer Theorem

The maximum power transfer theorem states that maximum power is transferred from a source to a load when the load resistance R_L equals the internal resistance R_i of the source.

An example of application of this theorem is that when connecting speakers to a stereo amplifier we use 8-ohm speakers on the 8-ohm output terminals of the stero. This match of load to source allows maximum transfer of power to the speakers. The internal resistance, or impedance, of a stereo amplifier is quite constant, however.

Photovoltaic Converter Internal Resistance Factors

Several factors can effect the internal resistance of a photovoltaic converter. The level of insolation striking the cells' surfaces is the main

cause of any change of this internal resistance. Temperature, however, has very little effect.

The ideal conditions for maximum possible power output from the converter are a bright sunny day and the sun's rays striking the cells' surfaces at 90 degrees. Change from these two ideal conditions will lower the output power, which indicates that the internal resistance has increased.

Factors which may lower the insolation striking the cells' surfaces include:

1. A high level of water vapor, or pollution, in the atmosphere.
2. Cloudy skies.
3. The time of day.
4. The time of year.
5. A change in the orientation of the converter itself.

Determining Photovoltaic Converter Output Power

Since a photovoltaic converter is a direct-current source, its output is real power which is measured in watts. The simpliest way to determine the converter's output power is to measure the voltage V_{RL} which it develops across the load resistance R_L and the output current I_o which it causes to flow through that load. Then the output power P_o in watts is the product of V_{RL} in volts and I_o in amps. Mathematically, the formula is $P_o = V_{RL} \times I_o$.

Graphic Illustration of Maximum Output Power

A simple method of illustrating that maximum output power occurs at a specific value of load resistance is to plot curves of V_{RL}, I_o and P_o values versus R_L values. Such a graph is shown in Figure 2.

For a photovoltaic converter the voltage will increase and then level off at higher load resistance. The current will begin at some high level and then drop off as load resistance increases. The output power, which is the product of voltage and current, will increase to a maximum (peak value) and then drop again as load resistance increases. The point where P_o peaks is where the source resistance R_i equals the load resistance R_L. Keep in mind, however, that R_i is not a fixed value but depends on several factors, as described earlier.

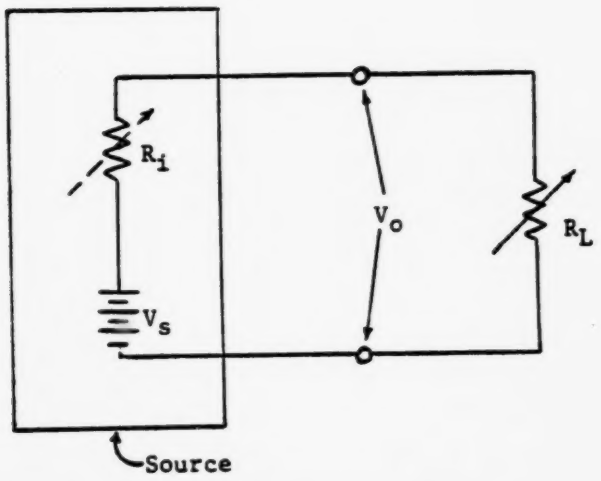


FIGURE 1. Schematic Symbol Sketch of Voltage Source with Internal Resistance.

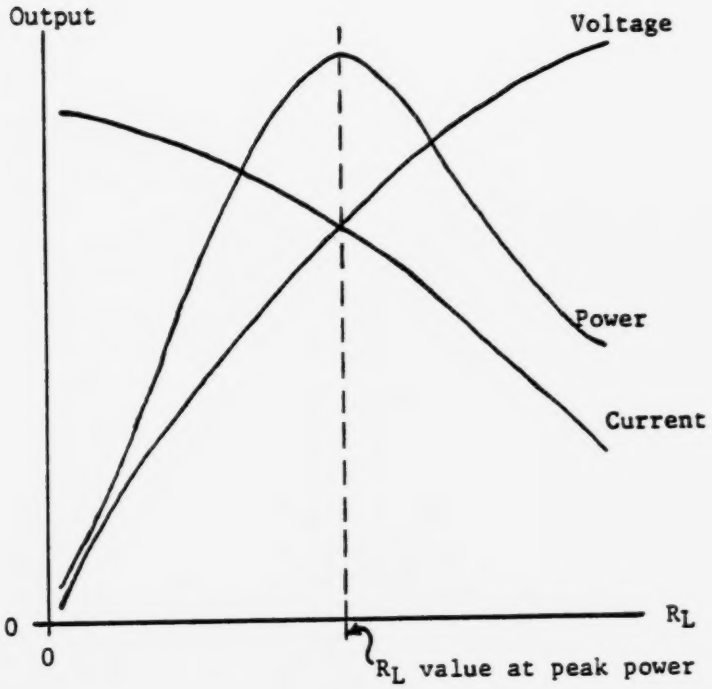


FIGURE 2. Illustration of Typical Curves of Voltage, Current, and Power Versus Load Resistance.

LEARNING ACTIVITIES
(MUST BE DONE ON A SUNNY DAY)

The following activities will acquaint you with the techniques by which the internal resistance of the photovoltaic converter module can be measured; first having full available insolation striking its surface and then having the isolation restricted.

1. Carefully move the solar electric generator system outdoors onto a level surface. Orient it, be rotating the chart, so that the converter is toward the sun. This position is achieved when the converter's shadow is centered on the width of the cart's top surface.
2. Place all six switches and the R_L leadwire in the following positions: S_1 -- OFF, S_2 -- Dummy Load, S_3 -- ON, S_4 through S_6 -- OFF, and R_L leadwire -- ∞ ohms.
3. Turn the voltmeter switch S_1 to the V_{RL} position and connect the R_L leadwire to the 1-ohm jack. This load resistance is the Beginning value, which appears in the top row in each of the tables on a following page.
4. Press and hold S_3 to keep it turned OFF while you read V_{RL} and I_o. Then record these in the 1-ohm row of Table A. Calculate the output power by $P_o = V_{RL}$ and I_o and record it in the proper column of the 1-ohm row of Table A.
5. Now connect the R_L leadwire to each successively higher load resistance jack and, in each case, repeat the readings, calculation, and recordings of step 4 above, ending with the last (15-ohm) jack for the R_L leadwire connection. Remember to hold S_3 OFF while reading the meters.
6. Now rotate the cart with solar electric generator system away from the sun to a point where the sun's rays strike the module's front surface at an angle of about 10 degrees to the module's surface.
7. Repeat steps 3, 4, and 5 above, but record the values in Table B.
8. The graph paper provided on a following page is for your plotting of the output power P_o versus load resistance R_L curve for each of the two conditions.
   a) First plot the points using the P_o and the R_L values of Table A and connect these points with a smooth line to form a smooth

curve. The curve should peak and appear similar to the power curve of Figure 2 earlier in this LAP. Label this curve the "Full Insolation" condition.

b) Second plot the points using the P_o and R_L values of Table B and connect these points with a smooth line to form a smooth curve. It should appear similar to the Power curve of Figure 2 earlier in this LAP. Label this curve the "Restricted Insolation" condition.

9. You now have all the information and the graphs needed to determine the module's internal resistance R_i. View the power curves plotted plotted for step 8 above.

   a) The peak power for the "Full Insolation" condition occurs where $R_L = R_i =$ _____ ohms.

   b) The peak power for the "Restricted Insolation" condition occurs where $R_L = R_i =$ _____ohms.

10. Which of the two conditions produce the higher output power? Give reasons why a difference exists in the output power levels. _____

_____

_____

11. Briefly discuss how much difference existed between the R_i values recorded in step 11, which of the two is larger, and why. _____

_____

_____

_____

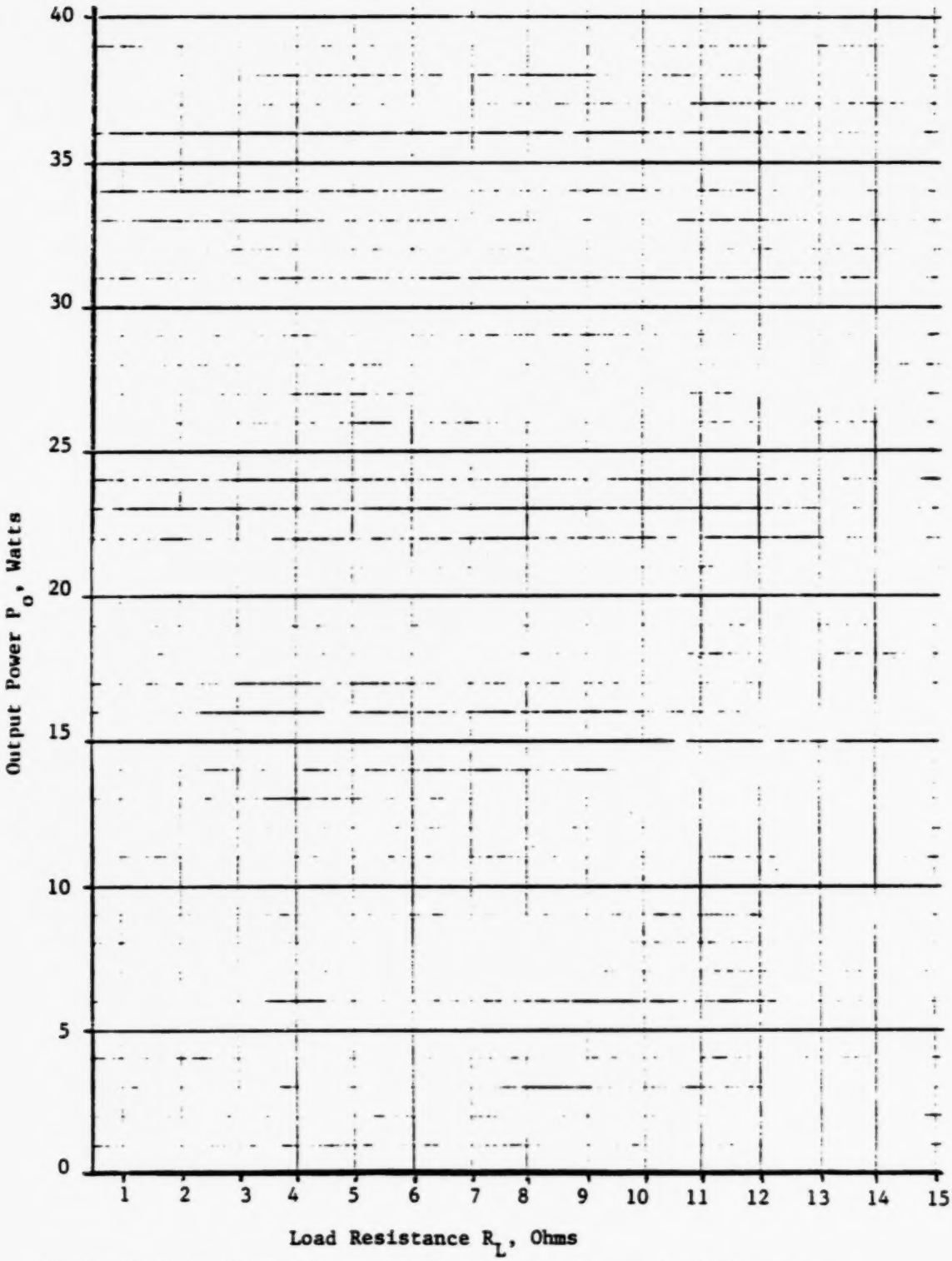
12. Place all six switches and the R_L leadwire to the positions given in step 2 above. Then return the solar electric generator system to its original location.

TABLE A
PHOTOVOLTAIC CONVERTER OUTPUTS
WITH FULL INSOLATION INPUT

Load Resistance R_L, Ohms	Load Voltage V_{RL}, Volts	Output Current I_o, Amps	Output Power P_o, Watts
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			

TABLE B
PHOTOVOLTAIC CONVERTER OUTPUTS
WITH RESTRICTED INSOLATION INPUT

Load Resistance R_L, Ohms	Load Voltage V_{RL}, Volts	Output Current I_o, Amps	Output Power P_o, Watts
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			



Graph of Photovoltaic Converter Output Power Versus Load Resistance

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Learning Activity Packet

MAJOR INSTRUCTIONAL UNIT: Photovoltaics

LEARNING ACTIVITY PACKET (LAP) NUMBER: 8

LAP TITLE: Photovoltaic Converter Output, Fixed-Position

PREREQUISITE LAP (S): 1, 2 and 7

LAP PURPOSE: To provide information on and experience in determining the output parameters of a photovoltaic converter when it is in the standard fixed-position orientation.

COMPETENCIES TO BE DEVELOPED:

1. Determine the standard conditions for a fixed-position installation of a photovoltaic converter.
2. Measure/determine the effects which the angle of incidence of the sun's rays has on the photovoltaic converter's output.
3. Measure and determine the insolation and input power and the output voltage, current and power when the photovoltaic converter is in the standard fixed-position orientation.

BACKGROUND INFORMATION

Fixed-Position Orientation

For most applications a solar electric generator system, or at least the photovoltaic converter itself, is installed or mounted in a fixed position. This is the least expensive type of installation because the converter is usually oriented due south and titled upward at a predetermined angle so as to favor a particular output power pattern throughout the year, and then is fastened in that position. It does not track the sun.

Converter Tilt Angle

The tilt angle of a photovoltaic converter is the angle between the back side of the converter and the horizontal. Converter tilt is necessary for most installations because the earth is titled at 23.5 degrees to the plane of its orbit around the sun. Thus, the sun is directly over head at mid-day on June 21st of each year at the Tropic of Cancer, which is at 23.5 degrees North Latitude.

The latitude angle, North or South, of any location on earth therefore becomes a reference for determining the tilt angle of the photovoltaic converter. One common practice for fixed-position orientation is to face the converter due south and tilt it at an angle equal to the latitude angle of the installation location. A map showing the latitude and longitude angles and Standard Time zones of the United States is shown in Figure 1. You should study this map to become familiar with the latitude and longitude angles of North Dakota. Sometimes, however, a tilt angle greater than the location's latitude is used so as to take greater advantage of the low angle of the sun's rays during our winter months.

Angle of Incidence

The angle of incidence is defined as the angle formed by an incoming ray of light and a line drawn perpendicular to the surface which the ray strikes. This is illustrated in Figure 2.

The photovoltaic converter will receive the maximum input (insolation) when the angle of incidence is 0 degrees. Under this condition it should also produce maximum output power. However, for any fixed-position installation the angle of incidence will change throughout the year and throughout each day. During each day the angle of incidence to the converter's surface will begin at some large value at sunrise, then reach a minimum at mid-day, and then increase again to some large value at sunset. Thus, any fixed-location

orientation of a photovoltaic converter will have lower output during the early morning and late afternoon than during mid-day.

Converter Input and Output Parameters

For any fixed-location orientation of a photovoltaic converter the input insolation can be measured by placing the insolation meter flat on the surface of the converter and reading the meter. Then the input power is obtained by P_i = Insolation x Total Cell Area. The units involved are Watts input = $mW/cm^2 \times cm^2$.

The angle of incidence of incoming rays is measured by placing the Angle of Incidence Meter flat on the surface of the converter. Then rotate its base on that surface and swing its sighting arm until the sunlight passes straight through both holes and causes a bright circular spot on the target plate below the holes. The angle of incidence is then read on the protractor. This meter is sketched in Figure 3.

The output power is determined by the same methods used in the previous Learning Activity Packet (LAP). The load resistance R_L is set at some suitable value. Then the load resistance voltage V_{RL} and output current I_o are measured. The output power P_o in watts is then calculated by $P_o = V_{RL} \times I_o$.

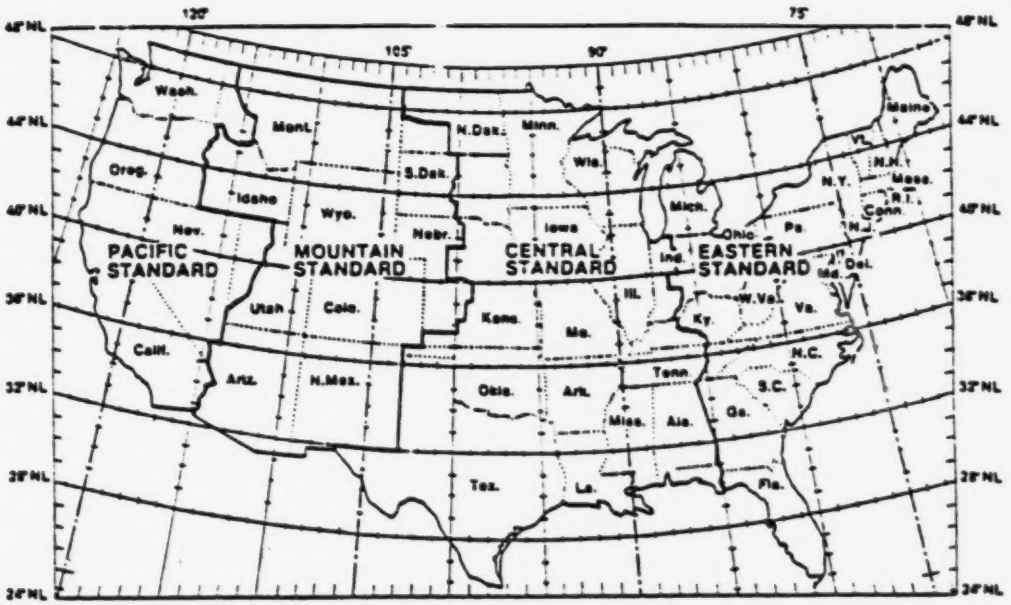

FIGURE 1. Latitude and Longitude Angles and Time Zones of the United States.

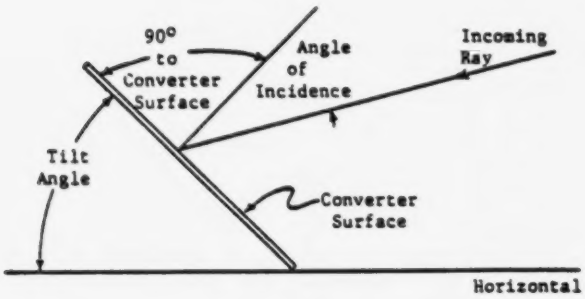

FIGURE 2. Illustration of Tilt Angle and Angle of Incidence.

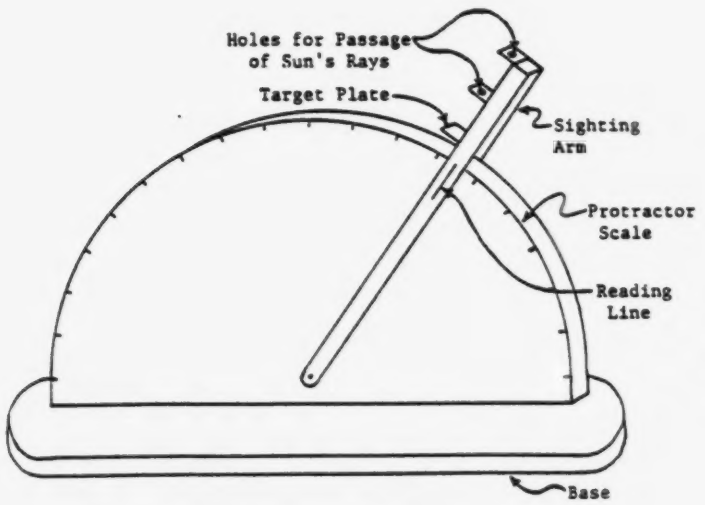

FIGURE 3. Sketch of Angle of Incidence Meter.

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LEARNING ACTIVITIES
(MUST BE DONE ON A SUNNY DAY)

Note A: The information gathering procedures of this Learning Activity Packet (LAP) should be done twice, once near solar noon when the sun's altitude is high and once in early forenoon or late afternoon when the sun's altitude is relatively low. The purpose of this is to detect any differences of input and/or output at these times of day.

Note B: Because this LAP uses "due south" orientation of the photovoltaic converter and LAP #9 uses "azimuth tracking" orientation, these two LAPs can be done at the same time on the same day. The only needed change is to rotate the solar electric generator system's cart back and forth for the two orientations.

1. Carefully move the solar electric generator system outdoors onto a level surface. Orient it so the front surface of the photovoltaic converter (module) is due south as accurately as reasonably possible. This is done by rotating its cart on the level surface.
2. Place all six switches and the R_L leadwire in the following positions:

   S_1 -- OFF, S_2 -- Dummy Load, S_3 -- ON, S_3 through S_6 -- OFF, and R_L leadwire --∞ ohms.
3. Turn the voltmeter switch S_1 to the V_{RL} position and connect the R_L leadwire to the 7-ohms jack. This will provide a suitable load resistance for the remaining parts of this LAP, and for LAP #9.
4. For the sake of having a record of approximately when the readings of this LAP were taken, record the clock time, Central Standard Time (CST) or Central Daylight Time (CDT) and date of these readings.
   a) Near Solar Noon clock time of readings = _____ ____.
   b) Early Forenoon or Late Afternoon clock time of readings = _____ ____.
   c) Date = _____ ___, 19___.
5. Using the insolation meter, placed flat on the front surface of the module, read and record the insolation I_a striking the module.
   a) Near Solar Noon I_a = _____ mW/cm^2.
   b) Early Forenoon or Late AFternoon I_a = _____ mW/cm^2.

6. Using the area of one cell, the number of cells of the module, and the I_a values recorded in step 5 above calculate the module's input power P_i by $P_i = 0.001 \times I_a \times$ Area of one cell x Number of cells.
   a) Near Solar Noon P_i = _____watts.
   b) Early Forenoon or Late Afternoon P_i = _____watts.
   Note: The 0.001 multiplier is needed to convert milliwatts to watts,

7. Using the angle of incidence meter measure the angle of incidence. Do this for both the near solar noon and for the early forenoon or late afternoon times of day. Record these angles in the spaces below.
   a) Near Solar Noon Angle of Incidence = _____degrees.
   b) Early Forenoon or Late Afternoon Angle of Incidence = _____degrees.

8. Press and hold S_3 OFF while you read V_{RL} and I_o. Record these below.
   a) Near Solar Noon V_{RL} = _____ volts and I_o = amps.
   b) Early Forenoon or Late Afternoon V_{RL} = _____ volts and I_o = _____ amps.

9. Using the formula $P_o = V_{RL} \times I_o$, calculate and record the module's output power.
   a) Near Solar Noon P_o = _____watts.
   b) Early Forenoon or Late Afternoon P_o = _____watts.

10. After viewing the values of input power, angle of incidence, load resistance voltage, output current, and output power of steps 4 through 9 above briefly describe the effects which time of day have on the fixed position photovoltaic converter's performance. ____

_____

_____

_____

_____

_____

11. Place all six switches and the R_L leadwire to the positions given in step 2 above. Then return the solar electric generator system to its original location.

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Learning Activity Packet

MAJOR INSTRUCTIONAL UNIT: Photovoltaics

LEARNING ACTIVITY PACKET (LAP) NUMBER: 9

LAP TITLE: Photovoltaic Converter Output, Azimuth Tracking

PREREQUISITE LAP (S) : 1,2,7 and 8

LAP PURPOSE: To provide information on and experience in determining the output parameters of a photovoltaic converter when it tracks the azimuth angle of the sun.

COMPETENCIES TO BE DEVELOPED:

1. Determine the standard time of sunrise and sunset on the day when the photovoltaic converter is used in the azimuth tracking mode.
2. Measure and determine the solar rays' angle of incidence and the insolation and power input to the photovoltaic converter during azimuth tracking.
3. Measure and determine the output voltage, current, and power of the azimuth-tracking photovoltaic converter.

BACKGROUND INFORMATION

Solar Azimuth Tracking

In the previous Learning Activity Packet (LAP) we described the fixed-location orientation of a photovoltaic converter where the converter does not track the sun's incoming rays, but is faced due south at a fixed tilt angle.

Another approach to converter orientation is to have the converter track the aximuth angle of the sun. As shown in Figure 1, the azimuth angle is the angle in a horizontal plane between due south and the "east-west" position of the sun. When solar azimuth tracking is used the converter is usually given a tilt angle equal to the latitude angle of the location, as in the fix-position orientation described in the previous LAP.

Solar azimuth tracking will provide higher output power from the photovoltaic converter than the fixed-position orientation, especially during early forenoon and late afternoon hours. During these hours the angle of incidence to the converter is reduced compared to that of a fixed-position system. However, the angle of incidence is still not 0 degrees because of the altitude angle of the sun. As shown in Figure 1, the altitude angle is the angle between the horizontal and the "height" position of the sun.

Though some gain in output power from the converter is achieved by azimuth tracking, it is often not economically advantageous to use. This is because azimuth tracking requires sensors to sense the sun's location and a circuit and motor to properly drive the converter from east to west during daytime hours and return it eastward for the next day's tracking. Such a sensor-driver system must be very reliable, and thus is quite expensive. Both azimuth and altitude tracking would require two such sensor-driver systems, with very little additional output power gained from the converter.

Daily Insolation Pattern and Solar Noon

The pattern of insolation available to either a fixed-position or azimuth tracking converter is illustrated in the graph of Figure 2. Notice that both the sunny and cloudy days' curves are symmetrical about solar noon. Solar noon is the time when the sun is at its highest altitude.

The earth orbits about the sun in a elliptical path, which itself causes up to 15 minutes difference ahead or behind clock time during the year. Also, there is a 30 minute solar time difference from one side to the other of each Standard Time zone. Therefore, solar noon does not occur at a fixed clock time throughout any time zone nor throughout the year.

Table A contained in this LAP provides data which occurs at specific solar times for the 21st of each month for three different North Latitude locations. This table's information shows that:

1. 12 A.M. in Solar Time is solar noon, with the other listed hours' data symmetrical about solar noon.
2. The solar altitude position (angle) is maximum at solar noon.
3. The solar azimuth position (angle) is 0 degrees at solar noon.
4. Both the solar altitude and azimuth maximum and therefore the solar positions at sunrise and sunset, change throughout the year.

Converter Input and Output Parameters

The measurements and calculations for determining the input insolation and power and the output voltage,current, and power for a solar azimuth tracking converter are the same as used for the fixed-position orientation. The only differences to expect are higher values or both input and output at times away from solar noon.

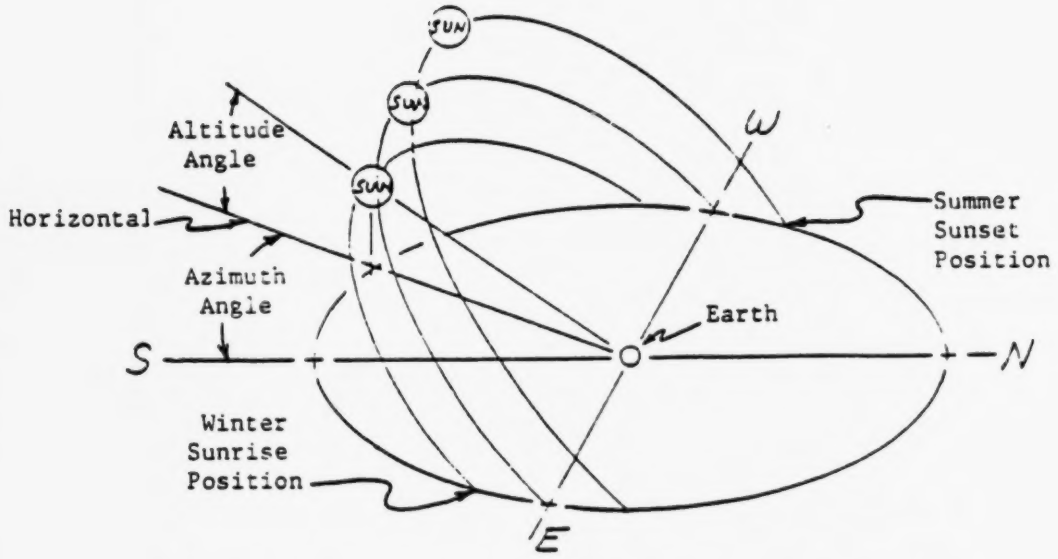

FIGURE 1. Illustration of Altitude and Azimuth Angles of the Sun and Seasonal Sunrise and Sunset Positions.

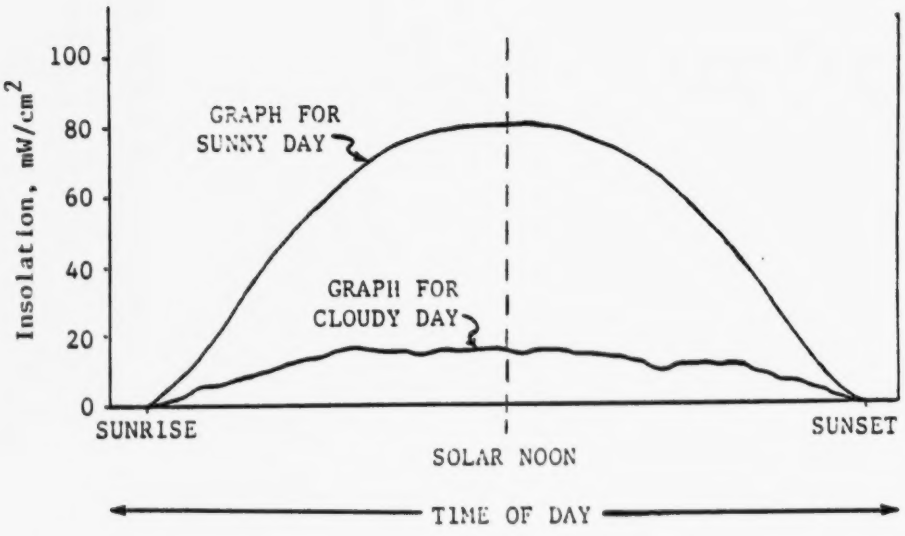

FIGURE 2. Daily Insolation Pattern Centered Around Solar Noon.

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TABLE A

Solar Position and Intensity Data for 32°, 40°, and 48° North Latitude

Date	Solar Time A.M.*	32° N. Latitude			40° N. Latitude			48° N. Latitude		
		Solar Position		Total Insolation BTU/sq. ft. Rad. N.**	Solar Position		Total Insolation BTU/sq. ft. Rad. N.**	Solar Position		Total Insolation BTU/sq. ft. Rad. N.**
		Alt.	Azm.		Alt.	Azm.		Alt.	Azm.	
Jan. 21	7	1.4°	65.2°	1						
	8	12.5	56.5	202	8.1°	55.3°	141	3.5°	54.6°	36
	9	22.5	46.0	269	16.8	44.0	238	11.0	42.6	185
	10	30.6	33.1	295	23.8	30.9	274	16.9	29.4	239
	11	36.1	17.5	306	28.4	16.0	289	20.7	15.1	260
	12	38.0	0.0	309	30.0	0.0	293	22.0	0.0	267
Feb. 21	7	6.7	72.8	111	4.3	72.1	55	1.8	71.7	3
	8	18.5	63.8	244	14.8	61.6	219	10.9	60.0	180
	9	29.3	52.8	287	24.3	49.7	271	19.0	47.3	247
	10	38.5	38.9	305	32.1	35.4	293	25.5	33.0	275
	11	44.9	21.0	314	37.3	18.6	303	29.7	17.0	288
	12	47.2	0.0	316	39.2	0.0	306	31.2	0.0	291
Mar. 21	7	12.7	81.9	184	11.4	80.2	171	10.0	78.7	152
	8	25.1	73.0	260	22.5	69.6	250	19.5	66.8	235
	9	36.8	62.1	289	32.8	57.3	281	28.2	53.4	270
	10	47.3	47.5	304	41.6	41.9	297	35.4	37.8	287
	11	55.0	26.8	310	47.7	22.6	304	40.3	19.8	295
	12	58.0	0.0	312	50.0	0.0	306	42.0	0.0	297
Apr. 21	6	6.1	99.9	66	7.4	98.9	89	8.6	97.8	108
	7	18.8	92.2	206	18.9	89.5	207	18.6	86.7	205
	8	31.5	84.0	256	30.3	79.3	253	28.5	74.9	247
	9	43.9	74.2	278	41.3	67.2	275	37.8	61.2	269
	10	55.7	60.8	290	51.2	51.4	286	45.8	44.6	281
	11	65.4	37.5	296	58.7	29.2	292	51.5	24.0	287
	12	69.6	0.0	298	61.6	0.0	294	53.6	0.0	289
May 21	5				1.9°	114.7°	1	5.2°	114.3°	41
	6	10.4°	107.2°	118	12.7	105.6	143	14.7	103.7	162
	7	22.8	100.1	211	24.0	96.6	216	24.6	93.0	218
	8	35.4	92.9	249	35.4	87.2	249	34.6	81.6	248
	9	48.1	84.7	269	46.8	76.0	267	44.3	68.3	264
	10	60.6	73.3	279	57.5	60.9	277	53.0	51.3	274
	11	72.0	51.9	285	66.2	37.1	282	59.5	28.6	279
	12	78.0	0.0	286	70.0	0.0	284	62.0	0.0	280

Source: Reprinted by permission from *ASHRAE Handbook of Fundamentals*, 1972.

Note: Make appropriate interpolations for the latitude of your own region.

* P.M. values mirror the A.M. values; 8 A.M.–4 P.M., 9 A.M.–3 P.M., 10 A.M.–2 P.M., etc.

** Radiation on a normal surface, representative of conditions on average cloudless days. The water content of the atmosphere can cause this to vary as much as 40%.

Date	Solar Time A.M.*	32° N. Latitude			40° N. Latitude			48° N. Latitude		
		Solar Position		Total Insolation BTU/sq. ft. Rad. N.**	Solar Position		Total Insolation BTU/sq. ft. Rad. N.**	Solar Position		Total Insolation BTU sq. ft. Rad. N.**
		Alt.	Azm.		Alt.	Azm.		Alt.	Azm.	
Jun. 21	5				4.2	117.3	21	7.9	116.5	77
	6	12.2°	110.2°	130	14.8	108.4	154	17.2	106.2	172
	7	24.3	103.4	209	26.0	99.7	215	27.0	95.8	219
	8	36.9	96.8	244	37.4	90.7	246	37.1	84.6	245
	9	49.6	89.4	263	48.8	80.2	262	46.9	71.6	260
	10	62.2	79.7	273	59.8	65.8	272	55.8	54.8	269
	11	74.2	60.9	278	69.2	41.9	276	62.7	31.2	273
	12	81.5	0.0	280	73.5	0.0	278	65.4	0.0	275
Jul. 21	5				2.3	115.2	2	5.7	114.7	42
	6	10.7	107.7	113	13.1	106.1	137	15.2	104.1	155
	7	23.1	100.6	203	24.3	97.2	208	25.1	93.5	211
	8	35.7	93.6	241	35.8	87.8	241	35.1	82.1	240
	9	48.4	85.5	261	47.2	76.7	259	44.8	68.8	256
	10	60.9	74.3	271	57.9	61.7	269	53.5	51.9	266
	11	72.4	53.3	277	66.7	37.9	274	60.1	29.0	271
	12	78.6	0.0	278	70.6	0.0	276	62.6	0.0	272
Aug. 21	6	6.5	100.5	59	7.9	99.5	80	9.1	98.3	98
	7	19.1	92.8	189	19.3	90.0	191	19.1	87.2	189
	8	31.8	84.7	239	30.7	79.9	236	29.0	75.4	231
	9	44.3	75.0	263	41.8	67.9	259	38.4	61.8	253
	10	56.1	61.3	275	51.7	52.1	271	46.4	45.1	265
	11	66.0	38.4	281	59.3	29.7	277	52.2	24.3	271
	12	70.3	0.0	283	62.3	0.0	279	54.3	0.0	273
Sep. 21	7	12.7°	81.9°	165	11.4°	80.2°	149	10.0°	78.7°	131
	8	25.1	73.0	240	22.5	69.6	230	19.5	66.8	215
	9	36.8	62.1	272	32.8	57.3	263	28.2	53.4	251
	10	47.3	47.5	287	41.6	41.9	279	35.4	37.8	269
	11	55.0	26.8	294	47.7	22.6	287	40.3	19.8	277
	12	58.0	0.0	296	50.0	0.0	290	42.0	0.0	280
Oct. 21	7	6.8	73.1	98	4.5	72.3	48	2.0	71.9	3
	8	18.7	64.0	229	15.0	61.9	203	11.2	60.2	165
	9	29.5	53.0	273	24.5	49.8	257	19.3	47.4	232
	10	38.7	39.1	292	32.4	35.6	280	25.7	33.1	261
	11	45.1	21.1	301	37.6	18.7	290	30.0	17.1	274
	12	47.5	0.0	304	39.5	0.0	293	31.5	0.0	278
Nov. 21	7	1.5	65.4							
	8	12.7	56.6	196	8.2	55.4	136	3.6	54.7	36
	9	22.6	46.1	262	17.0	44.1	232	11.2	42.7	178
	10	30.8	33.2	288	24.0	31.0	267	17.1	29.5	232
	11	36.2	17.6	300	28.6	16.1	283	20.9	15.1	254
	12	38.2	0.0	303	30.2	0.0	287	22.2	0.0	260
Dec. 21	8	10.3	53.8	176	5.5	53.0	88			
	9	19.8	43.6	257	14.0	41.9	217	8.0	40.9	140
	10	27.6	31.2	287	20.7	29.4	261	13.6	28.2	214
	11	32.7	16.4	300	25.0	15.2.	279	17.3	14.4	242
	12	34.6	0.0	304	26.6	0.0	284	18.6	0.0	250

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LEARNING ACTIVITIES
(MUST BE DONE ON A SUNNY DAY)

Note A: The information gathering procedures of this Learning Activity Packet (LAP) should be done twice, once near solar noon when the sun's altitude is high and once in early forenoon or late afternoon when the sun's altitude is relatively low. The purpose of this is to detect any differences of input and/or output at these times of day.

Note B: Because this LAP uses "azimuth tracking" orientation of the photovoltaic converter and LAP #8 used the "fixed position" orientation, these two LAPs can be done at the same time on the same day. The only needed change is to rotate the solar electric generator system's cart back and forth for the two orientations.

1. Carefully move the solar electric generator system outdoors onto a level surface. Orient it, by rotating the cart, so that the converter is toward the sun. This azimuth tracking orientation is achieved when the converter's (module's) shadow is centered on the width of the cart's top surface.
2. Place all six switches and the R_L leadwire in the following positions:
   S^1 -- OFF, S_2 -- Dummy Load, S_3 -- ON, S_4 through S_6 -- OFF, and R_L leadwire -- ∞ ohms.
3. Turn the voltmeter switch S_1 to the V_{RL} position and connect the R_L leadwire to the 7-ohms jack. This will provide a suitable load resistance for the remaining parts of this LAP, and for Lap #8.
4. For the sake of having a record of approximately when the readings of this LAP were taken, record the clock time, Central Standard Time (CST) or Central Daylight Time (CDT) and date of these readings.
   a) Near Solar Noon clock time of readings = _____ ____.
   b) Early Forenoon or Late Afternoon clock time of readings = _____ ____.
   c) Date = _____ ___, 19___.
5. Using the insolation meter, placed flat on the front surface of the module, read and record the insolation I_a striking the module.
   a) Near Solar Noon I_a = _____ mW/cm^2.
   b) Early Forenoon or Late Afternoon I_a = _____ mW/cm^2.

6. Using the area of one cell, the number of cells of the module, and the I_a values recorded in step 5 above calculate the module's input power P_i by $P_i = 0.001 \times I_a \times$ Area of one cell x Number of cells.
   a) Near Solar Noon P_i = _____watts.
   b) Early Forenoon or Late Afternoon P_i = _____watts
   Note: The 0.001 multiplier is needed to convert milliwatts to watts.

7. Using the angle of incidence meter measure the angle of incidence. Do this for both the near solar noon and for the early forenoon or late afternoon times of day. Record these angles in the spaces below.
   a) Near Solar Noon Angle of Incidence = _____degrees.
   b) Early Forenoon or Late Afternoon Angle of Incidence = _____degrees.

8. Press and hold S_3 OFF while reading V_{RL} and I_o. Record these below.
   a) Near Solar Noon V_{RL} = _____ volts and I_o = _____ amps.
   b) Early Forenoon or Late Afternoon V_{RL} = _____ volts and I_o = _____ amps.

9. Using the formula $P_o = V_{RL} \times I_o$, calculate and record the module's output power.
   a) Near Solar Noon P_o = _____watts.
   b) Early Forenoon or Late Afternoon P_o = _____watts.

10. After viewing the values of input power, angle of incidence, load resistance voltage, output current, and output power of steps 4 through 9 above briefly describe the effects which time of day have on an azimuth tracking photovoltaic converter's performance. _____

_____

_____

_____

_____

_____

11. After comparing the values of input power, angle of incidence, load resistance voltage, output current, and output power of steps 4 through 9 in LAP #8 with those of this LAP #9, briefly describe any differences between the fixed position orientation and the azimuth tracking orientation performance and why they might be significant.

12. Place all six switches and the R_L leadwire to the positions given in step 2 above. Then return the solar electric generator system to its original location.

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Learning Activity Packet

MAJOR INSTRUCTIONAL UNIT: Photovoltaics

LEARNING ACTIVITY PACKET (LAP) NUMBER: 10

LAP TITLE: Photovoltaic Converter Output Storage System

PREREQUISITE LAP (S): 1, 2 and 5

LAP PURPOSE: To provide background information and experience regarding the functioning of the storage system associated with a pohtovoltaic converter.

COMPETENCIES TO BE DEVELOPED:

1. Measure the storage battery voltage under no-load and loaded conditions.
2. Measure/determine the photovoltaic converter's output level which casues charging, matched-load, and discharging conditions for the storage battery.

BACKGROUND INFORMATION

The Need for Energy Storage

The energy storage part of a solar electric generator system typically consists of one or more nickel-cadmium or lead-acid batteries. The number of batteries making up this storage depends upon the quantity of storage needed to power the load through any anticipated period of time during which the available insolation is insufficient to recharge the batteries. Thus, the storage system size depends upon many factors, including:

1. The voltage, current, and power required by the load.
2. The frequency and time duration during which the load requires power.
3. The anticipated cold temperatures to which the batteries will be subjected, which determines their effectiveness in powering the load.
4. The anticipated durations of cloudy days, during which the insolation will be insufficient to charge the batteries.
5. The mean (average) number of hours of sunshine available at the installation location (see Table A in this LAP).

Storage Battery Ratings

Both lead-acid and nickel-cadmium batteries have a variety of ratings which may need consideration when designing the energy storage part of a solar electric generator system. Several of these ratings will be described here.

1. Capacity: The C-Rating indicates the product of current (amperes) which a battery can deliver and the time (hours) duration over which it can deliver that current. The C-Rating is determined by battery size and construction, and the units are Ampere-Hours.

   Two references are used in this rating, depending upon the intended application.

   a) The typical engine starting/ignition batteries are designed for applications involving repeated charge-discharge cycles of short duration, but where the discharge is not very "deep". These batteries use a time reference, usually 20 hours, for the C-Rating.

      An example of this is a 220 Ampere-Hour battery. It should deliver $\frac{220 \text{ Ampere-Hours}}{20 \text{ Hours}}$ = 11 Amperes over a 20 hour period of time.

b) The deep-charge/discharge cycle batteries are designed for applications involving repeated near-total discharge before recharge. Applications include electric golf carts, battery-powered automobiles, electric folk lifts, and solar electric generator system energy storage. These batteries use a constant current reference, commonly 75 amps for electric vehicle and 25 amps for marine applications, for the C-Rating.

An example of this is a GC 105 (Golf Cart 105 Minute) battery. It should deliver 75 amperes for 105 minutes. This would be equal to 75 Amperes x 1.75 Hours = 131.25 Ampere-Hours. Its voltage should not drop below 10.5 volts in this 105 minutes.

2. Energy Density: This is the ratio of the battery's energy storage capacity to the weight of the battery. Mathematically, this is: C-Rating x Battery Voltage/Weight = Amperes x Volts x Hours/Pounds = Watt-Hours/Pound.

3. Cycle-Life: This is the number of full charge and discharge cycles which the battery can endure without serious deterioration. This rating is only applicable to the "deep charge/discharge cycle" battery.

4. Temperature: All types of batteries perform differently at different temperatures. A nickel-cadmium battery's output capability increases with decreasing temperature, while the lead-acid battery's output declines as temperature decreases.

The lead-acid battery has an 80°F reference temperature for its other ratings. Its performance is greatly dependent upon both its temperature and the specific gravity of its electroyte, as shown in the listings below.

Temperature °F	% of Full C-Rating	Temperature °F	% of Full C-Rating
80	100	20	58
60	90	0	38
40	75	-20	15

Electrolyte Specific Gravity	Electrolyte Freezing Temp., °F	Electrolyte Specific Gravity	Electrolyte Freezing Temp., °F
1.275	-85	1.150	+ 5
1.250	-62	1.125	+13
1.225	-35	1.100	+19
1.200	-16	1.050	+25
1.175	- 4	1.000	+32

The above listings indicate that a battery's internal resistance R_i is a function of both temperature and level of charge. The concept of a voltage source's internal resistance was presented in Learning Activity Packet (LAP) #7.

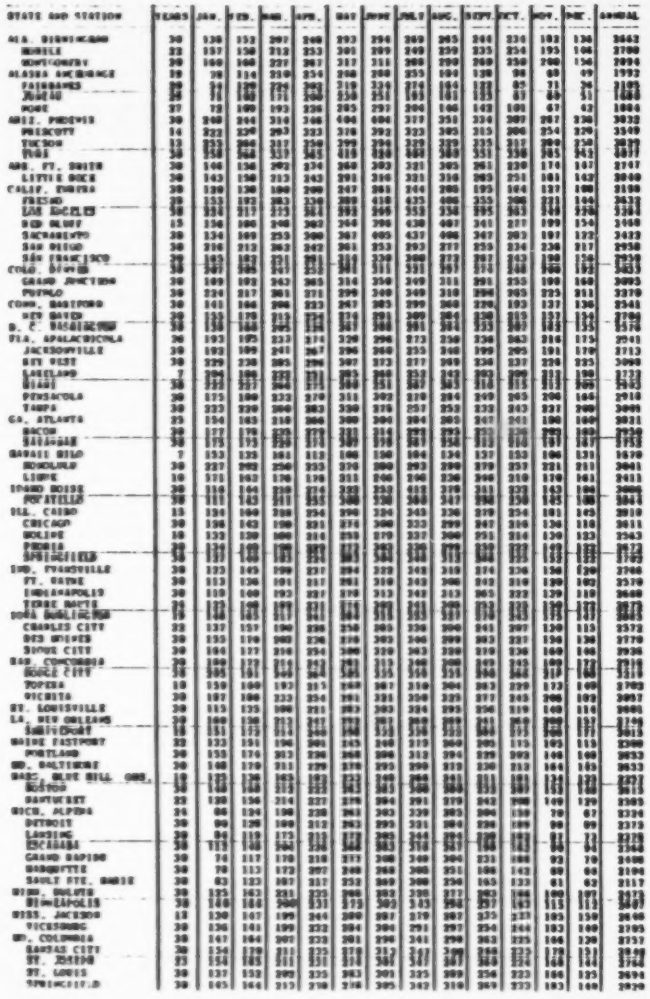
A battery's internal resistance can be determined by measuring its no-load voltage V_{nl} and then its loaded voltage V_l and load current I_l. Then its internal resistance in ohms is calculated by: $R_i = (V_{nl} - V_l)/I_l$

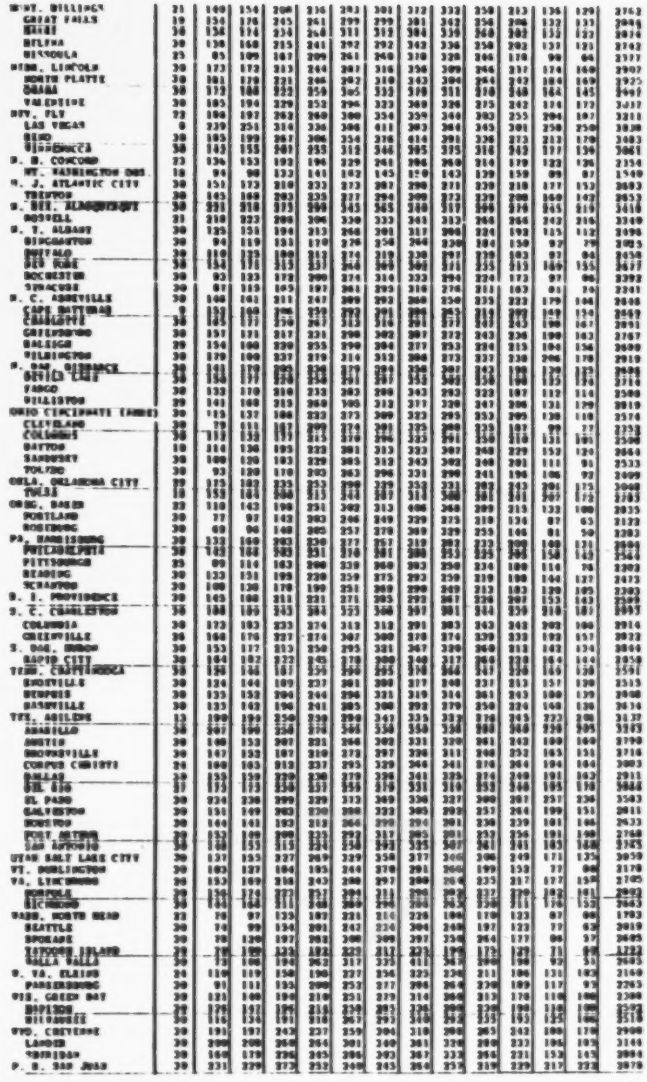
Safety Precautions

Both nickel-cadmium and lead-acid batteries use electrolyte which is extremely corrosive, damaging to skin, and very poisonous. Therefore, extreme caution must be exercised when working with these batteries. Also, both of these types of batteries give off gases, which can be highly explosive, during both charge and discharge. This is particularily true during high rates of charge or discharge. Therefore, the batteries should be ventilated, and not enclosed in any air-tight container or used where ignition of the gases is possible.

TABLE A

Mean Number of Hours of Sunshine





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LEARNING ACTIVITIES
(PART B MUST BE DONE ON A SUNNY DAY)

PART A: The learning activities of this part of this LAP will familiarize you with some of the characteristics of the storage battery contained in the experimental solar electric generator system you have been using. This part can be done indoors, or outdoors having the opaque cover over the module.

1. Place all six switches and the R_L leadwire in the following positions:

   S_1 -- OFF, S_2 -- Dummy Load, S_3 -- ON, S_4 through S_6 -- OFF, and R_L leadwire -- ∞ ohms.

2. Turn the voltmeter switch S_1 to the V_{bat} position and turn S_2 to the Charge/Discharge position.

3. Having S_4, S_5 and S_6 OFF as is indicated in the Reading Number 1 row of Table A, read and record the battery voltage V_{bat} in that row of the table. This is the no-load battery voltage.

4. Proceed to turn S_4, S_5, and S_6 ON or OFF in accord with each combination of switch positions of rows 2 through 6 of Table A. In each case read and record V_{bat} and the load current I in the corresponding rows of the table.

5. Now turn S_4, S_5, and S_6 ON as indicated in row 7 of Table A and then read and record V_{bat} and I_1 in that row of the table. These readings represent the loaded condition voltage and current.

6. Return all six switches and the R_L leadwire to the positions given in step 1 above.

TABLE A
STORAGE BATTERY LOADING DATA

Row or Reading Number	Discharge Load Switch Positions			Battery Voltage V_{bat}, Volts	Load Current on $I_{chg/dchg}$ Ammeter, Amps
	S_4	S_5	S_6		
1	OFF	OFF	OFF	V_{n1}	0.0
2	ON	OFF	OFF		
3	OFF	ON	OFF		
4	OFF	OFF	ON		
5	ON	OFF	ON		
6	OFF	ON	ON		
7	ON	ON	ON	V_1	I_1

7. Using the formula $R_i = (V_{nl} - V_l)/I_l$ calculate the internal resistance of the storage battery.

8. The C-Rating of the experimental solar electric generator system's storage battery is given on the side of the battery. Read and record that C-Rating here. _____

9. Using the load current I_l value of Table A and the formula Hours = Ampere-Hours/I_l calculate the time for which this battery should be able to deliver this level of load current.

PART B: The learning activities of this part of this LAP will indicate what portion of the load current I can be delivered by the photovoltaic module, represented by I_{mod}, when the module is connected to the battery and the two are loaded. This part must be done outdoors on a sunny day!

1. Carefully move the solar electric generator system outdoors onto a level surface. Orient it, by rotating the cart, so that the converter is toward the sun. This position is achieved when the converter's (module's) shadow is centered on the width of the cart's top surface.
2. Place all six switches and the R_L leadwire in the following positions:
   S_1 -- OFF, S_2 -- Dummy Load, S_3 -- ON, S_4 through S_6 -- OFF, and R_L leadwire -- ∞ ohms.
3. Turn the voltmeter switch S_1 to the V_{bat} position and turn S_2 to the Charge/Discharge position.
4. Proceed to turn S_4, S_5, and S_6 ON or OFF in accord with each combination of switch positions as listed sequentially in Table B. In each case read and record the module's output current I_{mod}, the load current I and the battery voltage V_{bat} in the corresponding rows of the table.

TABLE B

MODULE AND STORAGE BATTERY LOADING DATA

Row or Reading Number	Discharge Load Switch Positions			Module Current I_{mod}, Amps	*Load Current on $I_{chg/dchg}$ Ammeter, Amps	Battery Voltage V_{bat}, Volts
	S_4,	S_5	S_6			
1	ON	OFF	OFF			
2	OFF	ON	OFF			
3	OFF	OFF	ON			
4	ON	OFF	ON			
5	OFF	ON	ON			
6	ON	ON	ON			

*Indicate charging with C or discharging with a D just ahead of the recorded value.

4. When the readings for the last row have been recorded, return all switches and the R_L leadwire to the positions given in step 2 of Part B.

5. Viewing the $I_{chg/dchg}$ values recorded in Table B, for which load(s) did the module deliver enough load current to prevent discharge of the storage battery? _____

_____

_____

6. Viewing the V_{bat} values recorded in Table B, describe any changes which occurred during the entire sequence of increasing loading of the sytem. _____

_____

_____

_____

7. Return the solar electric generator to its original location.

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Learning Activity Packet

MAJOR INSTRUCTIONAL UNIT: Photovoltaics

LEARNING ACTIVITY PACKET (LAP) NUMBER: 11

LAP TITLE: Photovoltaic Converter Efficiency

PREREQUISITE LAP (S): 1, 2 and 7

LAP PURPOSE: To provide information and experience regarding the factors which effect the conversion efficiency of a photovoltaic converter.

COMPETENCIES TO BE DEVELOPED:

1. Make measurements for and determine the efficiency of the photovoltaic converter using different input power levels and different values of dummy-load resistance.
2. Make measurements for and determine the photovoltaic converter's efficiency during charging of the storage battery.

BACKGROUND INFORMATION

Photovoltaic Converter Efficiency

The efficiency of any energy or power converter is the ratio of its output to its input. Efficiency is usually expressed as a percentage. Therefore, working with units of power, this can be represented as % Power Conversion Efficiency = $P_o \times 100/P_i$.

Remember that output power P_o is the product of the voltage across the load V_{RL} and the output current flow through the load I_o. Also, the input power P_i received by the photovoltaic converter is the product of the insolation I_a striking the converter and the total area A of the converter's cells. Thus, the above equation can be written as:

% Power Conversion Efficiency = $V_{RL} \times I_o \times 100/I_a \times A$.

However, I_a is measured in milliwatts per square centimeter. Therefore the measured insolation I_a must be multiplied by 0.001 to convert it to watt units.

Efficiency Factors

Several factors can effect the efficiency of a photovoltaic converter, including:

1. The value of load resistance R_L effects efficiency. Maximum possible efficiency occurs when $R_L = R_i$, the converter's internal resistance.
2. The level of insolation I_a effects efficiency. This insolation, in turn, is effected by:
   a) The amount of water vapor, or pollution, in the atmosphere.
   b) The presence of thin, or thick, clouds in the sky.
   c) The time of day.
   d) The time of year.
   e) Any change in the tilt angle or other orientation of the converter itself.

Expected Efficiency

The present state-of-the-art of mass producing silicon photovoltaic cells limits their conversion efficiency. Typically, efficiencies of 12% to 15% are common. Precision laboratory manufactured and tested cells have produced efficiencies up to 20%, but such values would require ideal conditions in commercially available modules.

Experimental research being conducted by scientists and industries using materials other than silicon show promise for higher efficiencies. However, until these experimental materials are available in commercially available converters, silicon will remain as the dominant photovoltaic material.

LEARNING ACTIVITIES
(MUST BE DONE ON A SUNNY DAY)

The following activities will provide information regarding the efficiency of the photovoltaic converter (module) you have been using. Its efficiency will be determined under each of the conditions identified under B and F below.

A. Preliminary Activities:

1. Carefully move the solar electric generator system outdoors onto a level surface. Orient it, by rotating its cart, so that the sun's rays strike the back side of the module. This position will be used for conditions B and C below.
2. Place the six switches and the R_L leadwire in the following positions: S_1 -- OFF, S_2 -- Dummy Load, S_3 -- ON, S_4 through S_6 -- OFF, and R_L leadwire -- ohms.
3. Now turn S_4, S_5, and S_6 ON and leave them ON until condition E is begun. This will discharge the battery while you are covering conditions B through E, and thus permit a better representation of efficiency to show while charging the battery.

B. Condition of Restricted Insolation and 7-Ohm Load:

1. Turn the voltmeter switch S_1 to the V_{RL} position so as to measure the load voltage and connect the R_L leadwire to the 7-ohm jack.
2. Using the insolation meter, placed flat on the modules front surface, measure the insolation I_a reaching the module. Also determine the area of one cell and the number of cells in the module.
   Then using the milliwatt-to-watt correction formula
   $P_i = 0.001 \times I_a \times$ Area of one cell x Number of cells
   calculate the input power. P_i = _____ watts.
3. Press and hold S_3 OFF while reading V_{RL} and I_o. Then use the formula $P_o = V_{RL} \times I_o$ to calculate the output power. P_o = _____ watts.
4. Using the formula % Power Conversion Efficiency = $P_o \times 100/P_i$ calculate the photovoltaic converter's (module's) efficiency under these conditions.
   % Power Conversion Efficiency = _____%

C. Condition of Restricted Insolation And 15-Ohm Load: Leave the module as oriented for condition B above.

1. Repeat step B-1 above, except connect the R_L leadwire to the 15-ohm jack.
2. Repeat step B-2; P_i = _____ watts
3. Repeat step B-3; P_o = _____ watts
4. Repeat step B-4: % Power Conversion Efficiency = _____%

D. Condition of Full Insolation And 15-Ohm Load: Orient the module, by rotating its cart, so the sun's rays strike the front surface of the panel. This is achieved when the module's shadow is centered on the width of the cart's top surface.

1. Leave the R_L leadwire connected to the 15-ohm jack.
2. Repeat step B-2: P_i = _____watts.
3. Repeat step B-3: P_o = _____watts.
4. Repeat step B-4: % Power Conversion Efficiency = _____%.

E. Condition of Full Insolation And 7-Ohm Load: Leave the module as oriented for condition D above.

1. Repeat step B-1, except connect the R_L leadwire to the 7-ohm jack.
2. Repeat step B-2: P_i = _____watts.
3. Repeat step B-3: P_o = _____watts.
4. Repeat step B-4: %Power Conversion Efficiency = _____%.

F. Condition of Charging The Storage Battery: Leave the module as oriented for conditions D and E above.

1. Turn S_4, S_5, and S_6 OFF. Turn S_1 to the V_{mod} position to measure V_o. Turn S_2 to the Charge/Discharge position. Leave S_3 ON so the voltage regulator is in the circuit.
2. Repeat step B-2: P_i = _____watts.
3. Repeat step B-3 using V_o in place of V_{RL}: P_o = _____watts.
4. Repeat step B-4: % Power Conversion Efficiency = _____%.

G. Concluding Activities:

1. List the conditions and efficiencies obtained, in the order of highest to lowest efficiency.

2. Breifly describe factors which influenced several of the efficiency values which you determined. _____

3. Place all six switches and the R_L leadwire in the positions given in step A-2. Then return the solar electric generator system to its original location.

Affiliate of EXXON Enterprises, Inc.

Solar Electric Generator Systems

Principles of Operation and Design Concepts

SOLAR ELECTRIC GENERATOR SYSTEMS

Principles of Operation and Design Concepts

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I. Introduction

A. ENERGY FROM THE SUN

The sun is a nuclear power plant which generates power in the form of radiant energy at the phenomonally high rate of 3.8×10^{23} kilowatts. An extremely small fraction of this (less than a billionth) is intercepted by the earth, but this small fraction amounts to a huge 1.8×10^{14} KW. On the average, about 60% of this amount penetrates the atmosphere to reach the earth's surface (1.1×10^{14} KW). Of course, this amount of power is distributed over the entire surface of the earth. To bring these numbers closer to home, consider that on a bright sunny day each square meter of surface facing the sun receives about one kilowatt.

To compare these numbers with our energy needs, consider that the present electrical generating capacity in the U.S. is in the neighborhood of 5×10^8 KW (consumption is about half of this). This is equivalent to the average sunshine falling on only 1000 square miles. Even if we could only utilize 10% of the incident sunlight, a single square plot of land only 100 miles on a side would provide the same electrical power as the present U.S. generating capacity. Clearly, there is more than sufficient energy directly from the sun to meet present and future needs if we could learn to utilize it economically.

B. SOLAR CELLS

Direct conversion of solar energy can occur in two ways. The incident sunlight can be converted directly into heat by photothermal conversion, using a device which selectively absorbs the suns rays. A greenhouse is a crude form of this device. The incident sunlight can also be converted directly into electricity by photovoltaic conversion, using a device called a solar cell which utilizes the photoelectronic properties of a semiconductor. It is this device which is the basis for the business of Solar Power Corporation. Solar Power Corporation manufactures solar cells, constructs multicell modules, forms these into arrays, and designs complete systems to meet customers' needs. These systems are marketed worldwide. At today's costs, these markets are almost exclusively remote power applications such as microwave repeater stations, off-shore navigational aids, railroad grade crossing signals, and other applications that require reliable electrical power in locations not readily accessible to personnel or commercial power lines.

Basically a solar cell is a large area semiconductor diode, so constructed that light can penetrate into the region of the diode p-n junction. Silicon is used almost exclusively today as the semiconductor in commercially available solar cells. Certain impurities deliberately introduced into the silicon give rise to excess negative or positive charges which can carry electric current in the silicon. For example, phosphorous atoms give up electrons to the silicon to form n-type silicon (excess negative charges), and boron atoms soak up electrons from the silicon, leaving holes (missing electrons) which behave like excess positive charges (p-type silicon). A p-n junction can be formed close to one surface by allowing boron to diffuse into the surface of an n-type single crystal wafer at high temperatures. The p-n junction formed between the n-type silicon wafer and the p-type surface layer provides the electric fields which give rise to the diode characteristics as well as the photovoltaic effect. Light is absorbed in the silicon by generating both excess holes and electrons (one hole-electron pair for each photon absorbed). If this occurs near the p-n junction, the electric fields present there will act to separate the holes from the electrons, causing the holes to build up in the p-type material and the electrons in the n-type material. By connecting wires to the n and p-type regions, these excess charges generated by the light and separated by the junction can be made to flow through an external circuit to provide power to an external load. The operation of a solar cell is illustrated schematically in Figure 1.

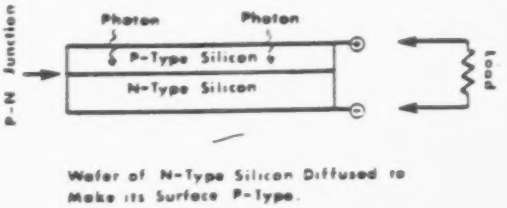

Figure 1. Schematic representation of a solar cell.

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Each cell can supply current at voltages up to one-half volt. At lower voltages the current supplied is nearly independent of voltage, but varies with light intensity. About 160 mA can be obtained from each square inch of surface exposed to bright sunlight. This would amount to over 1.5 amps from a 3.5 inch diameter cell. The maximum power deliverable to an external load is typically 11% to 12% of the total solar energy incident on the cell (over 15% has been demonstrated in laboratory models). To obtain higher voltages, cells are connected in series; higher currents are obtained by connecting cells in parallel. Such connections are made when cells are packaged in modules. The modules then become the building blocks for arrays designed to meet specific needs of cutomers.

In order for the solar cell to work as described, the silicon surface must be accessible to the incident light. Therefore the exposed surface cannot be covered with a metal conductor. However, metal contact to the surface is needed to pick up the current, so at least part of the surface must be covered. The trick is to cover as little of the surface as possible while providing sufficient current-carrying capacity and widespread distribution of pickup points over the surface to avoid any significant power dissipation in the contacts. For this reason the contact is put down in the form of a grid. A typical solar cell with grid contact is pictured in Figure 2.

Figure 2. Typical solar cell showing electrode grid pattern

C. ENERGY STORAGE

The total energy received from the sun in one year at any specific location on the earth is amazingly constant. The variation from year to year is less than 10%. However, within one year large variations occur both seasonally and daily, much of which is unpredictable. To avoid power outages at night and during inclement weather, some means of storing the energy generated on sunny days must be employed. All photovoltaic generator systems in use today employ rechargeable electric storage batteries for this purpose. Therefore, standard solar cell modules are designed to provide the correct output voltage to efficiently charge these batteries. The solar generator array is designed to provide all the energy required by the load over the year. The storage battery acts as a buffer between the solar array and the load, supplying power to the load during periods of low sunlight (and no sun) and accepting charge from the array during periods of high sunlight. Therefore, its state of charge may vary seasonally as well as daily: the average sunshine during the winter may be insufficient to supply the load, but this insufficiency will be made up by an excess of sunshine during the summer.

The capacity of the storage battery must be chosen to meet these demands. The storage battery also serves conveniently to fix the voltage at which the system will operate.

D. SOLAR GENERATOR SYSTEMS

In addition to a properly sized solar cell array and storage battery, a complete solar electric generator system will include a blocking diode to prevent battery current drain through the solar cell array at night. In complete darkness, the solar array is simply a string of diodes which would be forward biased by the storage battery. The blocking diode between the solar array and battery (Figure 3) allows current to flow from the array to the battery, but not from the battery to the array.

A voltage regulator may also be included in a complete system to avoid overcharging the battery, which results in a loss of electrolyte. This will occur when the battery is fully charged, but the solar array is still supplying more power than the load demands. Under these conditions, the voltage regulator will shunt the excess current through a dummy load. A voltage regulator may not be essential for systems which are not expected to supply a large excess of energy over the year, and if the customer is willing to visit the site in late summer to replace any lost electrolyte. However, a voltage regulator is recommended for all systems which are expected to produce over 20% excess energy over the year. The electrical schematic for a complete system is shown in Figure 3.

The following sections describe the concepts and methods used in designing or choosing the various components of the solar electric generator system. The concepts and methods used to determine the most economical complete system which meets the customer's needs (system sizing) are also described.

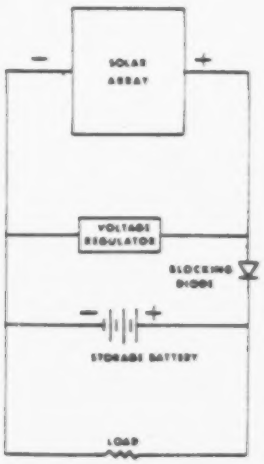

Figure 3. Electrical schematic of a complete solar electric generator system.

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II. System Components

A. MODULE DESIGN

It is common to describe the size of solar photovoltaic arrays in terms of their peak power output; i. e., the maximum power that can be delivered to a matched load when the incident sunlight is 100 mW/cm^2. However, by itself, this is not a significant parameter in the design of a solar array battery charging system. Both the current and the voltage characteristics of the solar array must be considered in conjunction with the battery voltage characteristics to obtain a proper match between the two. This means that the power must be supplied to the battery at a high enough voltage to fully charge the battery. For a typical 12-volt lead-acid battery, this voltage can range up to slightly over 14 volts.

I-V curves for a typical Solar Power Corporation M12-369 solar cell module with 100mW/cm^2 incident sunlight are shown in Figure 4. Both curves were obtained from the same module, but the temperature of the solar cells in the module was different, as indicated. The maximum power point of each curve is indicated by the arrow. This module contains 36 cells of 100mm diameter, all connected in series, and was designed for charging a 12-volt lead-acid battery. Note that the solar module behaves essentially as a constant current source nearly independent of voltage below the maximum power point, but that current falls off rapidly with increasing voltage above the maximum power point. The voltage at which this falloff occurs depends on the number of cells connected in series (and on their temperature). By choosing 36 cells, the module can supply the fully rated current of 2.0 A to the battery even when it is almost fully charged (14 volts charging voltage) at cell temperatures up to 60°C, and while accommodating voltage drops of about 0.3 V across a blocking Schottky diode and 0.3 V across the cable leads. This allows the nominal current rating of this module to be used in sizing systems without temperature derating for most applications. Although an additional cell in series (37-cell module) would cause the current drop-off to occur at higher voltage, and increase the power rating of the module and its cost, no benefit would be derived for charging the standard 12-volt battery.

As shown in the figure, the voltage falloff occurs at lower voltage as the temperature of the solar cells increases. The amount of this shift in falloff voltage is given approximately by 0.5% per degree celcius. By this means, temperature derating of modules can be taken into account when sizing systems.

In most applications, weather conditions are such that cell temperatures will rarely exceed about 60°C, and modules are designed for these normal applications. However, applications are occasionally encountered where climatic conditions lead to cell temperatures reaching 65 to 70°C. For example, in low altitude tropical locations, ambient temperatures may reach 40 to 45° C in season. Under these high temperature conditions, the cell temperatures will

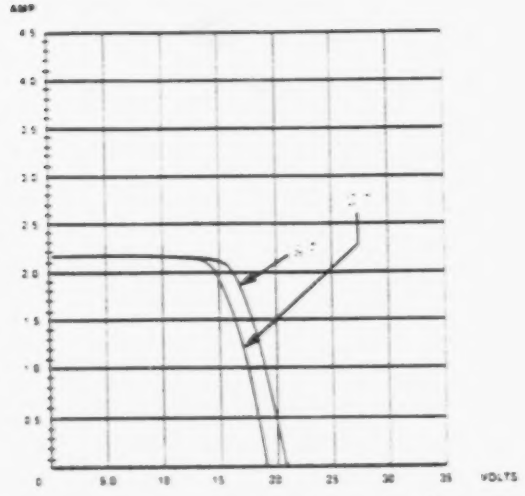

Figure 4. I-V Curves of Solar Power Corporation Module M12-361

exceed ambient by 20 to 25° C, and derating of modules (even 36-cell modules) should be taken into account when sizing systems. Usually the result will not effect the system design because this derating occurs at the time of the year when the battery has been brought to full charge by the excess sunlight. Therefore, there is no justification to design a special module with one or two extra cells in series for these special applications.

The constant charging current nature of a solar cell array properly matched to the storage battery allows system sizing to be computed in terms of ampere hours. This is very convenient because this quantity is very nearly conserved in a storage battery. Ampere hours out almost equals ampere hours in, even though power out is less than power in (amps come out at a lower voltage than they go in). In addition, the current supplied by the solar array is directly proportional to the incident sunlight. This does not affect the constant current nature of the solar array with respect to voltage; one should imagine the entire I-V Curve moving up and down along the current axis in direct proportion to the changes in sunlight intensity. This feature leads to a direct correspondence between integrated sunlight data and total ampere hours supplied by the array, independent of the sunlight intensity.

The current level obtained from a module of series-connected cells, as shown in Figure 4, is the same as that obtainable from a single cell in the module; this in turn, is determined by the exposed surface area of the cell. To obtain lower current levels than those shown, the module would have to be built with smaller diameter cells, such as Solar Power Corporation E-365 and P1002 modules. However, the number of series-connected cells to match a given storage battery is independent of cell size. Higher current levels can be obtained either by using larger cells, if they are available, or by connecting modules in parallel. In the latter case, the total current obtained is the sum of the current from the individual modules. This does not change the voltages at which the current drops off, which is fixed by the number of cells in series in each module. For

example, two identical modules connected in parallel would give the identical curve shown in Figure 4 if the current scale were doubled.

Different battery voltages are accommodated by connecting modules in series. If one module is properly sized in voltage for a 12-volt storage battery, then two such modules in series would be properly sized for a 24-volt battery. Thus, a specific application may require modules to be connected both in series and in parallel: series-connected to match the specific battery voltage, and additional modules connected in parallel to provide the required current generating capacity. The procedure for determining the required current generating capacity, called sizing the system, is described elsewhere.

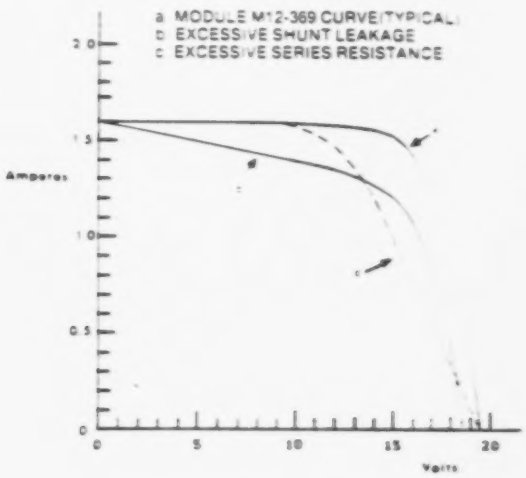

Figure 5. Effect of Shunt Leakage and Series Resistance on I-V Curves

The arguments on module design in this section were based specifically on the I-V Curve shape shown in Figure 4, which is typical of modules using solar cells manufactured by Solar Power Corporation. However, other solar cells may give rise to different curve shapes which could modify the arguments for the number of series-connected cells to charge a 12-volt battery. In Figure 5, Curve a. is a repeat of the solid line curve of Figure 4. If this module had been constructed of cells having excessive current leakage, the I-V Curve would look something like Curve b. in Figure 5. In this case, the nominal current rating of the module would have to be specified at a lower value, and conceivably it might be advantageous to put additional cells in series to minimize further derating at higher cell temperatures. If the module were constructed of cells having excessive series resistance, the I-V Curve would look something like Curve c. in Figure 5. In this case, it is clear that additional series-connected cells would be advantageous to reduce the very large derating which this module would exhibit at higher cell temperature. Also, the direct correspondence between integrated sunlight data and total ampere hours supplied by the module would no longer be independent of sunlight intensity, unless the number of series-connected cells were increased by about 25% for the case shown. This would seriously impact its cost. Thus, knowledge of the detailed shape of the I-V Curve is essential for proper module design.

B. BATTERY SYSTEM DESIGN

The major factors influencing the adaptation of storage batteries for use with solar panels are: the battery type required, the voltage, the ampere-hour capacity, and the environment in which it will be operating.

The two most common types of batteries used in solar electric generator systems are lead-acid and nickel-cadmium. The choice of battery type is usually specified by the customer. It is important in the case of lead-acid batteries that low self-discharge type batteries be used. For lead-calcium or pure lead grid constructions, losses are generally 1% of rated capacity per month. Lead-calcium types are preferred due to their higher mechanical strength. Lead-antimony grid types are not suggested since initial self discharge is 7 to 8% of rated capacity per month, and as the battery ages this figure rises to as much as 30 to 40% of capacity per month. Self-discharge loss becomes a load to the solar array and will increase the size of the solar panel without providing any power benefits to the user.

Battery capacity must be specified for the environmental conditions to which the battery will be exposed. Batteries are normally rated for operation at normal temperatures (between 0 and 30°C). When the battery cannot be insulated from abnormally cold temperatures (e. g., -20 to -40°C) by burial or placement is an insulated enclosure, it is necessary to derate its capacity. It cannot be allowed to discharge to the point where the electrolyte will freeze. The derating factor can be obtained from the known variation of freezing temperature with the specific gravity of the electrolyte shown in the following chart.

Freezing Points of Lead-Acid Battery Electrolyte:

Specific Gravity (at 25°C)	Freezing Point (°C)	Specific Gravity (at 25°C)	Freezing Point (°C)
1.300	-71	1.181	-22
1.283	-71	1.164	-18
1.266	-60	1.147	-15
1.249	-51	1.130	-12
1.232	-40	1.115	-10
1.215	-32	1.100	-8
1.198	-27		

One other factor influencing the selection of a battery is its charging efficiency. Up until the battery reaches 90% of full capacity, the solar panel charges the battery essentially in a constant current fashion. Therefore, the solar panel designer need only be concerned with ampere-hour charging efficiency of the battery. This efficiency is typically 95% acceptance or greater at normal temperatures. The bulk of the charging inefficiency manifests itself in the form of voltage level. The battery requires a higher voltage to accept a certain number of ampere-hours than it provides when the same ampere hour capacity is drawn off. Also, as the battery cools down, the charging voltage

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increases. However, this is offset by the fact that the silicon solar cell I-V Curve extends farther out on the voltage scale as temperature decreases.

As the battery reaches and exceeds 90% of capacity the solar array current decreases rapidly with increasing voltage. If the solar panel voltage (i.e., number of cells in series) and current outputs have been carefully matched to the load, this will provide a self regulating mechanism. However, when the solar array outputs exceed the load requirements by more than 20%, an external voltage regulator may be required to avoid excessive overcharging of the battery. This situation can arise because of the incremental changes in array output when modules are added to the array.

Batteries used with solar electric generator systems frequently operate under conditions which favor electrolyte stratification: the battery bank is stationary, and charging and discharging currents are low (typically less than 1% of battery capacity per hour). Under such conditions, it may be desirable to allow occasional mild gassing of the electrolyte to provide for mixing.

Nickel-cadmium batteries exhibit low self-discharge losses, and are more tolerant of accidents than are lead-acid batteries. For example, they will fully recover from freezing (the electrolyte becomes slushy) and from complete discharge to zero volts. Excessive overcharging will not damage the battery, but of course, the water lost from the electrolyte must be replaced. These advantages are often offset by high cost, voltage inefficiency (charging voltage 15% higher than discharging voltage, compared to a 5% change for lead acid batteries), and lower voltage per cell resulting in more cells to obtain a given battery voltage than lead-acid systems.

C. BLOCKING DIODE

To prevent current drain through the solar array at night, a blocking diode is connected between the battery and the solar array (Figure 3). Two types of diodes are used in Solar Power Corporation's systems: the p-n junction silicon diode and the Schottky barrier diode. Both are available with a wide range of current ratings. The Schottky barrier diode, while considerably more costly than the p-n device, has a low forward voltage drop of 0.4 volt as opposed to the p-n diode's 0.7 volt to 0.9 volt. This lower voltage drop allows a savings of one solar cell in each series string of the solar array. Therefore, the array is more efficient since not as much power is dissipated in the blocking diode.

For system voltages greater than 24 volts, however, a p-n junction diode should be used because the p-n diode can withstand higher reverse voltages than the Schottky diode. At night, the battery reverse biases the blocking diode. For maximum reliability, Schottky diodes are replaced by the higher reverse bias rated p-n junction diodes in systems of greater than 24 volts.

In addition to the concern shown for diode losses, all cable conductors and interconnecting wires for each array are of a sufficiently large wire gauge to insure that at 100 mW cm^2 incident intensity all resistance-caused voltage drops are less than 0.3 volt.

D. VOLTAGE REGULATOR

A voltage regulator is recommended for those systems that might otherwise experience excessive overcharging of the battery. The regulator has been designed so that the main solar array-battery system can work at maximum efficiency when the battery is less than fully charged. In this state, the regulator only consumes about 0.03 amp hour day and introduces no extra voltage drops in the system. When the battery voltage exceeds an adjustable preset level, the regulator proportions the current so that just enough passes into the battery to keep it fully charged and the remainder is shunted through a dummy load. The circuit schematic is shown in Figure 6. The normal system blocking diode is included in the regulator package when a regulator is supplied.

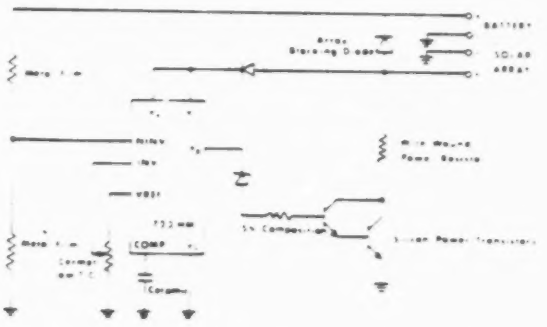

Figure 6. Typical Basic Voltage Regulator Circuit

Reliablity and stability have been designed into the voltage regulator. The parts count is kept low by using the 723 HM integrated circuit. This industry standard contains a stable voltage reference, a high gain differential amplifier, and an output stage with moderate current-handling ability. The temperature and long-term drift stability of this voltage reference, the 1% metal film resistors, and the cermet trim potentiometer used in this circuit account for the low overall drift of less than 0.02%/°C. The high gain amplifier provides tight regulation of better than 0.5% for 1 mA to full array current passing through the shunt path. The HM version of the 723 is a full military temperature range (-55° C to +125° C) device, hermetically sealed in a metal can. All components are operated far from their maximum ratings to assure long life, and the entire circuit board is coated with a moisture resistant film. If a failure were to occur, the most likely events would result in the shunt path being open circuited, leaving the solar array/battery system functioning in a normal, non-regulated manner.

The type of environment the regulator must withstand may have an impact on its cost. If the regulator cannot be placed in a location where it is protected from the weather, such as an equipment shelter, then a low-cost ventilated cabinet may be used. If the regulator is exposed to the elements, then a NEMA 12 type enclosure must be used and special provisions for mounting the heat dissipating

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components must be made to allow the heat to escape from the case.

Other designs have been investigated. A series pass element regulator requires less power dissipation capability with resulting lower cost. However, this type of regulator cannot have both low voltage drop (less than 1 volt) and low power requirements when the battery is in a low state of charge (regulator not needed). These two undesirable characteristics, series voltage drop and standby current drain, must be compromised in a series type regulator. Also, in the event of a failure, the most likely occurences will open the series element and not allow the array to charge the battery.

On off type regulators use relays or relay-like devices. Electro-mechanical relays are considered too unreliable due to their mechanical contacts. Solid state relays and other solid state switching devices exhibit fairly high voltage drops (~1 volt), requiring extra series-connected solar cells to be added to the array, increasing its cost without increasing the useful output of the array into the battery and load. Also, solid state relays exhibit the same type of failure modes as the series pass regulators do.

III. System Sizing

A. INSOLATION DATA

The amount of solar radiation received and the daily energy demand are the two controlling factors in the design of photovoltaic power systems. The selection of raw insolation data to be used in the design of a solar array system is dependent on the location and meteorological conditions prevailing between the data station and system location. Other contributing factors are the units in which the sunlight data is expressed, the source of the data (i.e., the recording agency), the various types of detecting instruments used, and the period over which the data was accumulated.

In most cases, a proposed solar array installation is located away from populated areas. Most of the solar radiation recording stations are centered around major cities or in populated locations. Therefore, selection of a suitable sunshine data station requires a careful match between both the climatic and geographical conditions. Since a few hundred miles separation between recording stations and installation location may have profound effects on prevailing sunlight conditions, factors such as terrain differences (mountain range, arid or heavily vegetated regions, proximity to large bodies of water), elevation differences, and physical distance must be weighted for each location. The aim in selecting a data station location is to find one with a similar climate, a close match in latitude (since tilted gain figures are a function of latitude) and longitude, and at least three years of accumulated data readings. Since the sunlight data is expressed as monthly average, day-to-day variations will be smoothed out over the month. Long term weather conditions resulting in abnormally heavy snow falls, rainy or overcast periods, and excessively dry, clear weather may occur during a given year, affecting monthly and yearly averages of the solar radiation data recorded. However, over several years, such occurances will tend to average out.

Sunlight data is available in many different forms. Weather services generally report the percentage of possible sunshine actually received day to day and the number of hours of sunshine received. This data is useful for determining the climatic conditions of an area, but is not normally used in the design of a solar electric generator, which requires a knowledge of the total energy received. Approximate energy figures could be obtained by making some assumptions about weather and sky conditions, but the results would be much less reliable than even short duration data recorded in energy units, and therefore is rarely used. Since the sunlight is a day-to-day variable, monthly and yearly averages are most adaptable to use in systems design.

Some of the commonly used energy units are BTU's per sq ft and calories per sq cm (Langleys). BTU's per sq ft are most commonly used by people designing solar thermal collectors, while the Langley is extensively used in the design of solar electric generators. However, other energy units are useful after the correct conversions have been made to more convenient forms.

Two final factors involved in the selection of a solar data station are the recording agency and the instrument used in obtaining the data. A publication by the University of Wisconsin has compiled solar energy data for many areas of the world entitled "World Distribution of Solar Radiation." For the most part, solar energy is recorded by the national meteorological and weather service. For the United States, the data is compiled by the Department of Commerce, Weather Bureau Climatological Center. For other areas of the world local weather services, the World Meteorological Organization (WMO), various university and private field installations, and in some cases, private individuals are the sources for insolation data.

The majority of instruments used in recording solar radiation are either thermo-electric or bi-metallic expansion types. Other instruments include devices that record solar radiation by means of discoloration of a wax coated chart. In the United States, Europe and Africa, the thermo-electric type recording instruments (pyranometers) are widely used. With a well maintained instrument, accuracies of 3% to 5% are obtainable. In South America and Asia, the bi-metallic expansion type instrument is more widely used. However, a well maintained bi-metallic expansion instrument will have a lower accuracy than the thermo-electric type. Deviations of at least ten percent (10%) or greater can be expected. The wax coated strip chart recorder and other similar instruments provide meaningful data only when the incident solar energy is at relatively high levels. They are unable to record lower level diffuse radiation which in some areas comprises a considerable portion of the insolation received. Generally, these types of data stations are not used in solar electric generator design.

B. WEATHER AND CLIMATIC DATA

In the design of solar electric generator systems, other climatic conditions apart from sunlight must be considered. Since the voltage of silicon solar cells is a temperature related parameter, the designer must be aware of the prevailing daily temperatures, both extremes (high and low) and seasonal variations. In addition, rain and snowfall must be considered in the design of the mounting structure. Wind loading is especially important in mountain top installations. Infrequent weather phenomena such as hail storms, electrical storms, and incidence of fog should also be investigated as to their effects on systems operation. For the United States, the Environmental Science Services Administration has compiled a "Climatic Atlas of the United States" listing much of the above data. Also, from the National Climate Center, the Weather Service publishes monthly summaries of the weather conditions at their stations located throughout the country. For other areas of the world, the data is not as extensive and is usually found in university studies or through the WMO records.

As in the case of sunlight stations, weather information must also be adapted to the specific installation area. Temperature is most commonly adjusted. Differences in elevation result in large temperature changes. Thorough design takes this into account and adjusted temperature data is substituted for the raw data.

C. COMPUTER AIDED SYSTEMS DESIGN

Solar Power Corporation has developed a pair of computer programs to aid in the design of solar electric generator systems. These programs are processed in our in-house computer. The programs can be operated in a totally automatic mode or they can be operated in a conversational mode where the operator (the solar electric generator designer) can ask for different systems to be visually displayed to satisfy special requirements. However, the purpose of the programs is to facilitate the selection of the optimum combination of solar cells and battery for a particular power requirement.

The first of the two programs is solely concerned with the conversion of raw insolation data from the horizontal or 0° tilt angle to other tilt angles. Only in the vicinity of the equator is a horizontal panel fully utilizing the available solar energy. As you move either north or south in latitude, the optimum angle of tile moves with you. For year round average, the best tilt angle is the same as the latitude of the installation location. However, generally during the summer months there is an excess of sunlight, while during the winter months the solar energy is at a low level due to the shift in the sun's position. By increasing the tilt angle of the solar panel (with respect to the horizontal) 5° to 15° more than the latitude, significant gains can be obtained during the winter months while sacrificing some of the excess energy received in the summer months. This procedure is not useful in every system, but in some cases it can reduce the size of the solar panel/battery system as illustrated in the example at the end of this section.

The computer uses as its raw insolation data, flat Langleys (cal sq cm) averaged over a month's time. This information along with the location name, its latitude, longitude, and elevation are also fed into the computer at the start of the design procedure. At this time, temperature values reflecting the adjustment for elevation or other geographical differences between recording station and use area are also entered. The computer then automatically returns a printout of equivalent daily Langleys for each month of the year and a yearly average for a user's specific tilt range. The designer can specify up to ten different tilts at five degree intervals.

The equivalent tilted Langley data is the combination of a derived gain factor and the flat Langley data. In calculating the gain factors, the computer goes through routines that develop numbers relating time of year and sun position to length of day. Two numbers are generated under length of day: the day length on a horizontal surface and the equivalent day length on a tilted panel. Combining the proper length of day for a specific tilt angle and the percentage of total daily energy received for each hour of the day with day length, a gain factor is generated. The above table combines factors for a solar position shifting and time of day energy variations into a single number. (See Fig. 7)

The above gain factor, if directly applied to the flat Langley data, would give very large gains during the winter months while showing only modest decreases in the summer months. This is due mainly to the type of energy received in these periods of the year. The two types of radiation, direct and diffuse, play a large part in determining the magnitude of the gain factor. Direct radiation can be improved significantly by alignment with the sun, but diffuse radiation is insensitive to orientation. The computer program developed by Solar Power Corporation has built-in correction factors for this diffuse light. The variation of diffuse light with both time of the year and latitude is also included automatically. The final output from the computer is a carefully adjustable table of the variation of insolation with regard to latitude, climate, diffuse radiation, and hemisphere. The last factor is important because the winter-summer gain factors occur in different months of the year in the northern and southern hemispheres.

When this data is generated, it becomes part of a permanent solar energy library. This library has been classified into three areas: North, Central, and South America; Europe, Africa, and the Mid-East; and Asia, Australia, and the Pacific Area. These classifications allow the designer to re-select specific data files from the library for use in new systems design. The library is also updated with new files when needed.

The second program that comprises the design package is concerned with the combination of customer power requirements, available solar energy for his installation area, climatic factors, available solar energy devices, and battery voltage, type, and capacity. In addition, this program generates a detailed Systems Design Report for the optimum system. Included in this report is information

on the data location used, the tilt angle of the array and the expected solar radiation for that tilt angle as it varies month to month, the expected solar electric generator output in ampere-hours per day, the average daily high temperature for the installation, and the average state of charge of the battery as it varies from month to month. In addition, the location of installation and the data stations, the model number of the solar array, and the suggested battery type and capacity are also provided. All of the above are generated automatically by the computer. In selecting the optimum system, the computer may run through many different combinations of tilt angle, solar cells, and batteries before the optimum system is found. In the automatic mode, these systems are not displayed to the designer. Only the final selection is displayed and printed. However, when a system requires special attention, the designer can go into a conversational mode and have more complete control over what types of systems are generated.

In both modes, the computer goes through a temperature derating routine in order to use current and voltage values in the various calculations that reflect the expected currents and voltages from the solar array at the installation site. At the same time, the effect of variation in the battery state of charge on its charging voltage is taken into account. The resulting currents and voltages are combined with the various corrected tilt angles to find the output of test arrays. The computer then offers the system to the designer for inspection.

In practice, the computer calculates the smallest possible solar panel for each tilt and power requirement. At the same time, the computer compares the solar array output against the load requirements and generates the battery capacity necessary to operate the system during periods of low sunshine. In addition, it is the design philosophy of Solar Power Corporation to include a specific number of "no sun days" of battery storage. A "no sun day" is one in which it is assumed the solar array provides no power to either the battery or the load. (In reality, the solar panel will provide some power even during heavy overcast days.) The number of "no sun days" is selected by the designer. In determining this number, a quick check of extended periods of overcast weather and a check of the climate in general is taken. For example, in desert or semi-arid regions, 5-days storage is generally added, while in areas of heavy fog with much coastal cloudiness, such as found in the North Sea or the Gulf of Mexico, 20 to 30 days are required. (U.S. Coast Guard regulations require the use of 30-days storage in offshore solar energy power systems.)

In calculating a "minimum" system, the solar panel must provide, on a yearly average, the customer's load plus an extra 10%. This added 10% allows for a bad year in sunshine, the self-discharge of the battery system (only when low loss batteries, 1% per month, are used), and other minor variations that may occur.

The computer program can handle systems of many different voltage and ampere-hour drains. It also has separate routines for derating depending on the type of storage battery specified (lead-acid, low and high self-discharge types, or nickel-cadmium type batteries). In addition, the computer can select a minimum battery capacity required when the battery is subjected to extremely low or high temperatures. Automatic oversizing can be selected to allow sufficient reserve capacity for when the battery is at its lowest state of charge and operating in temperatures from -20°C to -40°C.

All of the above procedures can be performed automatically when a system consisting of a constant daily load and no special environmental factors is designed. When a system with special conditions presents itself, the operator can take advantage of the computer's calculating speed while maintaining control over the important parameters.

SOLAR POWER CORPORATION
SYSTEMS DESIGN REPORT

DATE	10 17 78
QUOTE NUMBER	87178C
CUSTOMER	EXXON ENT INC
SALES REGION	1 - SOLAR POWER
ENGINEER	PGA
LOCATION	BOSTON MASS
DATA LOCATION	BOSTONMA
DATA LATITUDE	42 22 N
DATA LONGITUDE	71 W

MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
FLT LNGLYS	129	190	293	364	472	495	496	425	341	238	145	119
TEMP	0	5	5	10	20	25	25	22	20	15	10	5

TILT 65

LOAD 12.0 LOAD=10.0% 12.2 SERIES= 1 PARA= 2

MONTH	TEMP	LNGLYS	LOAD	OUTPUT	DFCTR	SURPL
JAN	0	285	12.00	11.2	24.8	0.0
FEB	5	316	12.00	12.5	0.0	14.1
MAR	5	369	12.00	14.6	0.0	80.6
APR	10	344	12.00	13.6	0.0	46.0
MAY	20	362	12.00	14.3	0.0	71.1
JUN	25	347	12.00	13.7	0.0	51.9
JUL	25	359	12.00	14.1	0.0	65.1
AUG	25	365	12.00	14.3	0.0	71.2
SEP	20	382	12.00	15.1	0.0	92.8
OCT	15	359	12.00	14.2	0.0	68.1
NOV	10	299	12.00	11.8	6.0	0.0
DEC	5	278	12.00	10.6	43.4	0.0
AVE/TOT	22	337	12.00	13.3	74.2	562.6

SAFETY FACTOR 11.0% TOTAL MODULES 2

MODEL M012-0002-369

LOW SUN STORAGE	74 AMPS
15 DAYS STORAGE	180 AMPS
TOTAL/@ 100 HP RATE	254 AMPS

LEAD ACID BATTERY SYSTEM

Figure 7. Computer printout of system sizing data

An example of system sizing is shown in the computer printout reproduced in Figure 7. This is for a 12 V system located in Boston, MA. The load is a constant 12 amp-hours per day. The first row of data (FLT LNGLYS) shows the average daily number of Langleys incident on a flat surface each month. The second row (TEMP) is the average daily high temperature (°C) for each month, which is used for temperature derating of modules when required. From this input data, the computer picks the optimum system of solar modules, battery capacity, and array tilt angle which provides at least 10% in excess of the load requirement over the year, and prints the output data shown in the columns.

In the example shown, the computer has chosen a solar array consisting of two Model M12-369 modules, wired 1 in series, 2 in parallel, and has chosen to tilt the array 65° from the horizontal, facing due south. The first column (TEMP) repeats the temperature data in the second row. The second column (LNGLYS) gives the average daily number of Langleys incident each month on a surface tilted

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at 65°. The third column (LOAD) is the constant 12 amp-hours/day load of this example. The fourth column (OUTPUT) is the average daily output of the solar array each month, in amp hours. Depending on whether the output is greater or less than the load, there will be a surplus or a deficit each month. These are recorded in the last two columns, headed DFCTS and SURPL, as the total amp hours for the month. For example, in January the average output is 11.2 amp hours/day, which is 0.8 amp hour/day less than the load requires. The total deficit for January is therefore, 0.8 amp hour/day x 31 days = 24.8 amp hours. The last entry in these two columns is the sum of the monthly deficits and surpluses for the whole year. The total deficit for the year becomes the "low sun" storage component of battery capacity. To this is added 15 days of "no sun" storage (12 amp hours/day x 15 days = 180 amp hours) to give the total required battery capacity of 254 amp hours. The net surplus (total surplus minus total deficit) is 11% more than the load requires, which just exceeds the design requirement of at least 10% oversize.

Based on the monthly deficit and surplus, the expected variation in state of charge of the battery can be deduced. The result is plotted in Figure 8. The accumulation of deficits during the winter months leads to the partial discharge of the battery during that period as shown. The provision for 15 days "no sun" storage is also indicated.

The maximum output over the year from a solar array with a fixed tilt occurs when the tilt is approximately the same as the latitude of the location. Therefore, one may wonder why the computer didn't pick a tilt angle closer to 42 degrees in the example shown. The reason becomes clear if we examine the data for a tilt of 45° (Figure 9). In this case, the same solar array is required (two Model M12-369 modules connected in parallel), and the net output over the year has increased from 11% oversize to 19.5% oversize. However, the total deficit accumulated over the winter months has also increased, almost doubling the low sun storage requirement on battery capacity (from 74 to 138 amp hours). Therefore, a larger and more expensive battery would be required. Since the additional output of the solar array tilted at 45° cannot be utilized in this application, it is clearly more economical to tilt the array at 65° and take advantage of the smaller storage battery this allows.

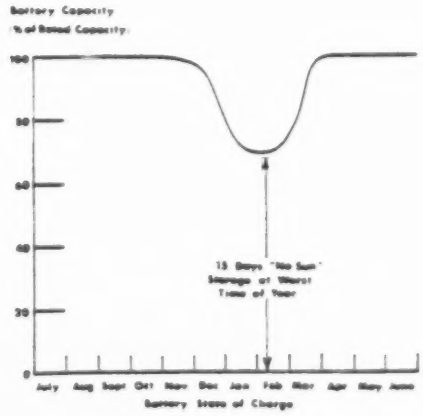

Figure 8. Battery State of Charge (monthly average)

TILT 65

MONTH	TEMP	LNGLYS	LOAD	OUTPUT	DFCTS	SURPL
JAN	9	195	12.00	11.2	.84	0.0
FEB	9	216	12.00	12.0	0.0	14.1
MAR	5	269	12.00	14.0	0.0	30.1
APR	16	344	12.00	15.1	0.0	61.2
MAY	28	401	12.00	14.2	0.0	93.3
JUN	28	347	12.00	12.1	0.0	93.4
JUL	28	395	12.00	14.1	0.0	124.1
AUG	28	361	12.00	14.1	0.0	154.2
SEP	28	285	12.00	10.2	0.0	167.4
OCT	15	259	12.00	14.1	0.0	197.5
NOV	16	209	12.00	11.1	0.0	208.6
DEC	9	178	12.00	10.6	47.4	0.0
AVE/TOT	22	277	12.00	12.1	48.1	741.6

SAFETY FACTOR 11 % TOTAL MODULES 2

MODEL M812-0002-369

LOW SUN STORAGE 74 AMPS

15 DAYS STORAGE 180 AMPS

TOTAL @ 180 HP RATE 254 AMPS

LEAD ACID BATTERY SYSTEM

TILT 45

MONTH	TEMP	LNGLYS	LOAD	OUTPUT	DFCTS	SURPL
JAN	9	266	12.00	10.6	47.4	0.0
FEB	9	299	12.00	12.2	0.0	5.6
MAR	5	373	12.00	15.1	0.0	39.7
APR	16	467	12.00	16.1	0.0	95.8
MAY	28	477	12.00	15.1	0.0	161.1
JUN	28	420	12.00	14.0	0.0	144.0
JUL	28	455	12.00	14.6	0.0	157.6
AUG	28	422	12.00	13.6	0.0	141.2
SEP	28	411	12.00	14.2	0.0	126.0
OCT	15	368	12.00	11.9	0.0	69.1
NOV	16	279	12.00	11.0	0.0	0.0
DEC	9	250	12.00	7.9	69.1	0.0
AVE/TOT	22	361	12.00	14.2	129.9	1000.0

SAFETY FACTOR 19 % TOTAL MODULES 2

MODEL M812-0002-369

LOW SUN STORAGE 138 AMPS

15 DAYS STORAGE 180 AMPS

TOTAL @ 180 HP RATE 318 AMPS

LEAD ACID BATTERY SYSTEM

D. FIELD SIZING TECHNIQUES

Sometimes it is desirable to obtain a quick field estimate of the solar array size required for a specific application. In many cases a reasonably good estimate can be obtained from a few simple calculations. The daily load (amp hr/day) must be obtained along with the yearly average of the daily sunlight incident at the proposed installation site. The incident sunlight (Langleys/day) can usually be obtained from a publication by the University of Wisconsin entitled "World Distribution of Solar Radiation". It is convenient to multiply the average number of Langleys/day by the factor 0.0116 to convert the total sunlight energy received during the day to an equivalent number of hours of peak sunlight (defined as 100 mW/cm^2). This is because module output specifications are quoted for incident peak sunlight of 100 mW/cm^2. Therefore, module output (amp hr/day) is simply its rated charging current output multiplied by the equivalent number of peak sunlight hours/day.

The total number of modules in the array is given by the number connected in series multiplied by the number connected in parallel. The number in series is known when the battery voltage of the application is specified. Most M series modules are made to match a pre-specified nominal system voltage such as a 12V lead-acid battery. A 12V system, therefore, requires one module in series, a 24V system requires two in series, and so on. For P1002 modules, a 12V system means 7 modules in series, a 24V system means 14 modules in series, and so on. The number of modules connected in parallel is obtained simply by dividing the daily load (amp hr/day) by the average daily module output (amp hr/day) as determined above. The following examples illustrate this procedure.

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EXAMPLE I—Series M Modules (model M12-369)

A 24v mountain top radio repeater located near Grand Junction, Colorado draws 6 amps when transmitting (20% of the time), but only draws 0.5 amp during standby and receiving (80% of the time). The daily load is therefore, 38.4 amps hrs/day.

Load = (6 amps x 4.8 hrs) + (0.5 amp x 19.2 hrs)
= 28.8 + 9.6
= 38.4 amp hrs/day

At Grand Junction, the annual average Langley reading is 454 Langleys/day. Multiplying by 0.0116 gives 5.27 equivalent hours of peak sunlight per day. The specifications for the M series module chosen indicate an output current of 1.62 amps at the battery charging point under peak sunlight conditions. Therefore, the average daily output of each module is 1.62 amps multiplied by 5.27 peak sunlight hours which gives 8.54 amp hrs/day.

Peak Sun Hr = 454 Langleys/day x 0.0116
= 5.27 hrs.

Module Output = 1.62 amps x 5.27 hrs.
= 8.54 amp hrs/day

The number of modules connected in parallel is obtained by dividing the load (38.4 amp hrs/day) by the module output (8.54 amp hrs/day), which gives 4.5 modules. Because fractional modules are not available, the next whole number of modules must be used (5 modules).

No. Parallel Modules = Load/Module Output
= 38.4/8.54
= 4.5
= 5 whole modules

Since this a 24 V system, there are 2 modules connected in series. The complete array will therefore, contain ten (10) M series modules.

Total Number = No. Series x No. Parallel
= 2 x 5
= 10 modules

EXAMPLE II—Model P-1002 modules

A railroad grade crossing near Laramie, Wyoming uses a 12 V system to power bells and lights. The system draws 6 amps when the crossing is occupied (1 hr/day), but only draws 0.6 amp on standby (23 hrs/day).

Load = (6 amps x 1 hr.) + (0.6 amp x 23 hrs.)
= 6 + 13.8
= 19.8 amp hrs/day

At Laramie, the annual average Langley reading is 407 Langleys/day, and the specifications for the P-1002 module indicate an output current of 0.60 amp under peak sunlight conditions.

Peak Sun Hr. = 407 Langleys/day x 0.0116
= 4.72 hrs.

Module Output = 0.60 amp x 4.72 hrs.
= 2.83 amp hrs./day

No. Parallel Modules = Load/Module Output
= 19.8/2.83
= 7.0 modules
= 7 whole modules

Since this is a 12 V system, there are 7 modules connected in series. The complete array will therefore contain forty-nine (49) P-1002 modules.

Total No. = No. Series x No. Parallel
= 7 x 7
= 49 modules

This quick array sizing procedure ignores several important factors such as effects of temperature and battery state of charge on module output, and effects of tilting the array. The net result is an estimate which will tend to err on the conservative side.

BATTERY CAPACITY

Only very rough estimates of required battery capacity can be made in the field. The system sizing procedure used in the field gives no indication of the seasonal deficits which will accumulate. A rough rule of thumb is given in the following table, which gives battery capacity in terms of the number of days of storage required for different latitudes. The table applies only to locations having normal weather conditions. The estimator must use his own judgment about local weather conditions. For example, locations such as Troy, New York and Seattle, Washington require an additional 5-days storage to be added to figure in the table.

Latitude	Days storage
0°—30°	15
30°—40°	20
40°—50°	25
50°—60°	30
60°+	35+

Battery capacity estimates obtained this way are likely to be conservative.

The actual battery capacity required is the number of days storage multiplied by the daily load of the system. In EXAMPLE I, this gives 20 days x 38.4 amp hrs/day = 768 amp hrs. battery capacity. In EXAMPLE II, this gives 25 days x 19.8 amp hrs/day = 495 amp hrs. battery capacity. (NOTE: Battery selection should be based on the capacity at the 100-hr. rating.)

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